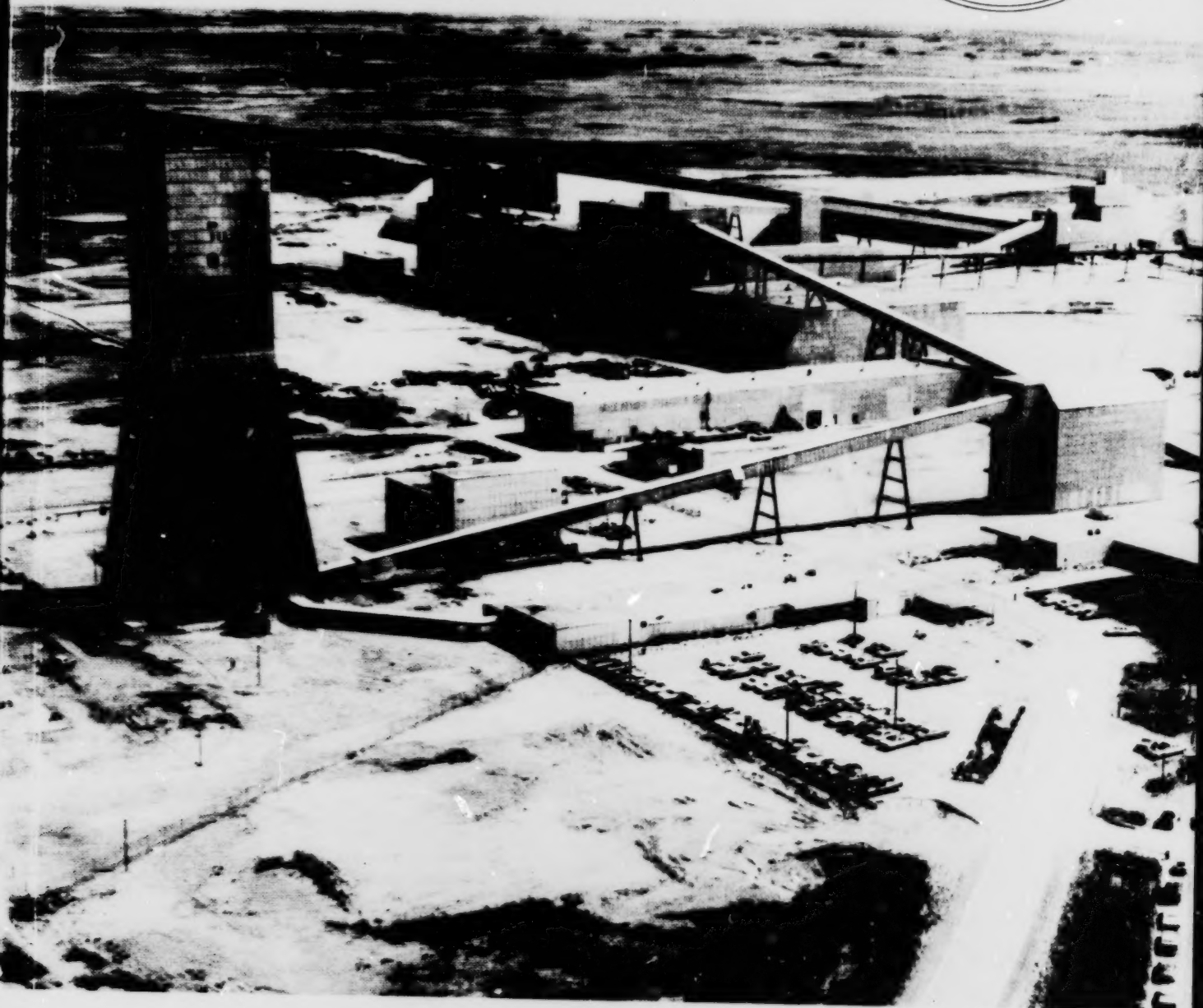


ECONOMIC MINERALS OF SASKATCHEWAN



Edited by C.F. Gilboy and L.W. Vigrass

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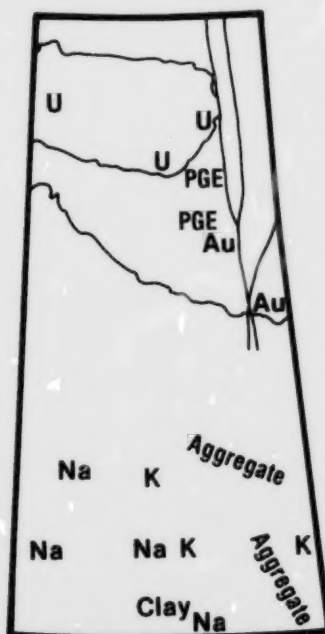
Proceedings of a Symposium held in Regina, November 17 and 18, 1986

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ECONOMIC MINERALS OF SASKATCHEWAN

Proceedings of a Symposium
Held in Regina, Saskatchewan
17 & 18 November 1986

EDITORS:
C.F. GILBOY and L.W. VIGRASS



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Aerial view of the headframe and mill complex, Potash Corporation of Saskatchewan Mining Limited, Lanigan Division (*Government of Saskatchewan photograph* taken in July 1977, when the mine was owned and operated by Alwinal Potash of Canada Limited).

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The S.G.S. currently promotes the earth sciences within Saskatchewan and outside the province as follows:

- Semi-monthly meetings (January to May, September to December), each featuring a distinguished geoscience lecturer
- Biennial symposia, generally with themes which focus on different aspects of Saskatchewan's economic geology
- Special publications, mostly symposia proceedings, but including field excursion guides, geological highway maps (an upcoming project) and other miscellaneous studies
- Field trips
- Partial sponsorship of science fairs throughout the province
- Talks to grade-school and high-school students, upon request
- Occasional public lectures
- Annual awards to the most promising earth sciences undergraduate at the Universities of Saskatchewan and Regina
- Annual Christmas lecture for Regina school students

FOREWORD

The papers contained in Economic Minerals of Saskatchewan were originally delivered to 197 delegates attending a Saskatchewan Geological Society conference held in Regina on November 17 and 18, 1986. They focus on those of the province's mineral commodities which are recovered mainly by mining and quarrying.

This publication commences with overviews of the regional geology of Saskatchewan's Precambrian and Phanerozoic rocks. The following ten contributions deal with metallic ores which contain platinum group elements, gold or uranium and which mostly occur in Precambrian rocks. They are succeeded by eight papers about commodities such as potash, kaolin, coal, sodium sulphate and gravel which are associated with Phanerozoic rocks.

We hope that the conference and the proceedings volume will stimulate further research into, and development of, Saskatchewan's economic mineral deposits.

We are grateful to the authors, who devoted both time and expertise towards producing high-quality papers. We thank the companies, academic institutions and government agencies which, in many different ways, helped to make the conference a success and this proceedings volume a reality. We greatly appreciate the assistance of Society members with proof reading and other tasks involved in the production of this book. Mike Thomas, who laid out and pasted up practically every page herein, deserves particular credit. Finally, we are indebted to our respective employers for providing us with the time required to edit the contents of Economic Minerals of Saskatchewan, which we consider to be a valuable addition to the province's geological literature.

C.F. Gilboy
(Saskatchewan Energy and Mines)

L.W. Vigrass
(University of Regina)

EDITORS' COMMENTS

- Editorial changes have been carefully made to try to avoid altering authors' original meanings, both factual and interpretative.
- Where languages other than English appear in the text, accents and other similar features have been omitted.
- Most illustrations are reproduced as submitted; unfortunately, a few lack complete clarity, especially if certain patterns of mechanical ornamentation were used on figures that required substantial reduction in size.

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Corporate support is an important source of Saskatchewan Geological Society funds, and enables the Society to maintain vigorously its wide variety of geoscientific activities. Such support is also valuable in that it confirms to individual members that our goals are shared by industry. The Society therefore acknowledges with deep gratitude the contributions it has received from the organizations listed above (Corporate Membership, \$100.00; Corporate Sponsorship, \$50.00; Corporate Donorship, \$25.00), and encourages others to join their ranks.

*Awarded by the S.G.S. Executive in acknowledgement of services rendered that greatly exceed in value the fee for the appropriate category of corporate support.

OVERVIEW OF THE PRECAMBRIAN GEOLOGY AND ASPECTS OF THE METALLOGENESIS OF NORTHERN SASKATCHEWAN

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ABSTRACT

This paper provides a broad overview of the geology of the Precambrian Shield of northern Saskatchewan and particularly emphasizes the results of recent radiometric age-dating work. It also focuses on aspects of the region's metallogenesis.

On a province-wide scale, three major geological subdivisions are identified:

- 1) an ensimatic regime made up of the Southeastern Complex and the La Ronge-Rottenstone Magmatic Belt,*
- 2) an ensialic regime represented by the Cree Lake Ensialic Mobile Zone and the Western Craton, and*
- 3) the Athabasca Basin, filled by unmetamorphosed, predominantly coarse fluvial and marine clastic rocks which unconformably overlie crystalline basement.*

Lower Proterozoic metallogenesis reflects the contrasting ensimatic and ensialic regimes. Volcanogenic base-metal and gold mineralization typifies the eugeoclinal volcanic-plutonic arc and interarc sequences of the former; sedimentogenic base-metal and uranium mineralization is characteristic of the miogeoclinal sequences which overlie the Archean basement in the latter. Reference is made to a major Hudsonian crustal feature which transects the Western Craton. It is characterized by high radiometric and low gravity signatures, and may have potential for granite-hosted tin-tungsten mineralization. The rich, economically important, unconformity-type uranium deposits of the Middle Proterozoic Athabasca Basin are described, as also are aspects of the diagenetic-hydrothermal model proposed for their formation. The question is raised as to whether the Basin also has potential to host economic concentrations of any of the diverse suite of elements typically associated with the uranium mineralization.

Northern Saskatchewan's various "gold camps" are identified, and their geology briefly examined. Historical gold exploration figures for Saskatchewan are contrasted with those of the established gold provinces of Quebec and Ontario. They seem to suggest that, to date, Saskatchewan has been relatively little explored and that the province's gold potential has yet to be fully realized.

INTRODUCTION

The crystalline basement of northern Saskatchewan is part of the Trans-Hudson Orogen which extends some 5000 km from Greenland to the mid-continental United States. It comprises Archean and Aphebian rocks variably influenced by Lower Proterozoic thermotectonic events.

In the northwest, the basement is overlain by red beds of the Martin Group. South of Lake Athabasca, the younger Athabasca Group also shows red-bed character and forms about one-third (100,000 km²) of the Shield area. The crystalline basement and overlying successions are cut by diabase dykes and sills probably emplaced in several generations between 1300 and 1000 Ma.

The basement comprises both ensialic and ensimatic portions of the Orogen developed respectively to the west and east of the Needle Falls Shear Zone. The major change in crustal

character between Lower Proterozoic continental-miogeoclinal and oceanic-eugeoclinal regimes has apparent continuity as a deep crustal conductivity anomaly beneath the Canadian Plains into Wyoming (Camfield and Gough, 1977), where it emerges as the Cheyenne Belt, a zone of major shearing in the Sierra Madre and Medicine Bow Mountains. Here, it separates the Archean Wyoming Craton and overlying miogeoclinal Snowy Pass Supergroup from an 1800 Ma arc-type terrain of southern Wyoming and Colorado (Hills and Armstrong, 1974; Karlstrom et al, 1983).

Four major crustal elements are generally recognized in the crystalline basement of Saskatchewan (Fig. 1):

- 1) the Southeastern Complex,
- 2) the La Ronge-Rottenstone Magmatic Belt,
- 3) the Cree Lake Ensialic Mobile Zone, and
- 4) the Western Craton.

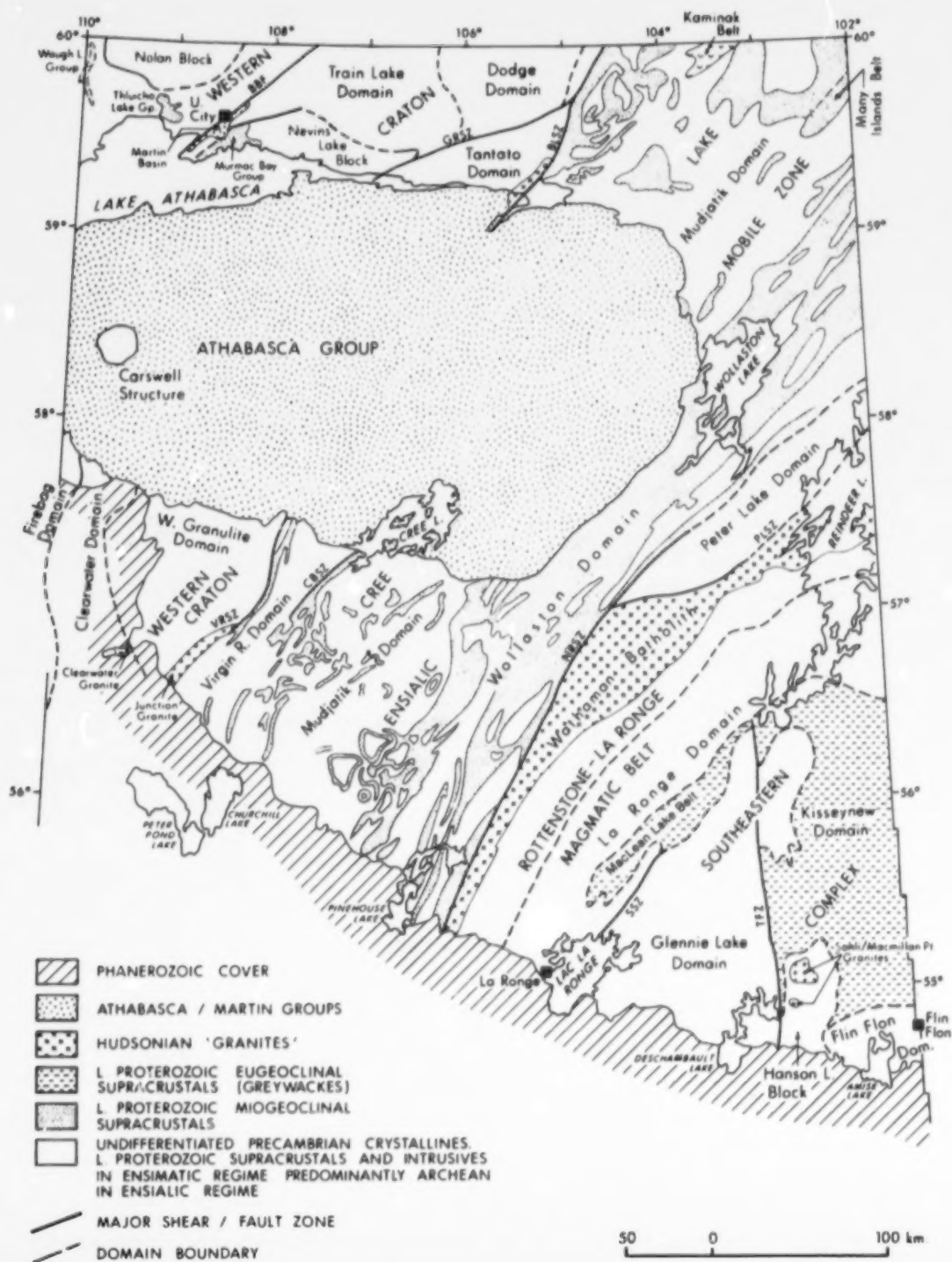


Figure 1. General geology and major subdivisions of the Precambrian in northern Saskatchewan. Major shear zones and faults: NFSZ - Needle Falls (Shear Zone), VRSZ - Virgin River, BLSZ - Black Lake, GRSZ - Grease River, CBSZ - Cable Bay, PLSZ - Peter Lake, SSZ - Stanley, BBFZ - Black Bay (Fault Zone), TFZ - Tabernor.

These can be further subdivided into various lithostructural domains, each of which shows broad internal homogeneity in its lithological, structural and metamorphic characteristics.

THE SOUTHEASTERN COMPLEX

The Southeastern Complex comprises several contrasting domains (Table 1).

The Flin Flon (Snow Lake) Domain is characterized by predominantly mafic volcanic rocks of the Amisk Group, disconformably overlain by coarse clastic rocks of the Missi Group and intruded by several ages of plutons of pre- and post-Missi age (Byers and Dahlstrom, 1954). It is generally interpreted as a Lower Proterozoic volcano-plutonic arc (Stauffer et al, 1975). The Amisk volcanics have been dated at 1885 Ma by R.R. MacQuarrie (unpublished data) using the U-Pb zircon method. The grade of metamorphism of these rocks is lower to upper greenschist facies.

The Kiseynew Domain is thought to represent an interarc volcanogenic sedimentary basin (Bailes and McRitchie, 1978; Lewry, 1981). It contains predominant pelitic and hornblende gneisses, representing greywackes and mixed intermediate to mafic with minor felsic volcanic and volcanoclastic rocks, and subordinate psammitic gneisses representing coarser, cleaner clastic rocks which locally overlie a basal polymictic conglomerate (Ashton et al, 1986). The former, equivalent to the Nokomis Group gneisses in Manitoba (Robertson, 1953), are equated by Ashton et al (1986) with the Amisk Group; the latter, equivalent to the Sherridon Group gneisses (Bateman and Harrison, 1946), possibly with the Missi Group. Grades of metamorphism are typically high, ranging from the upper amphibolite to the granulite facies. The junction between the two Groups is marked in part by mafic volcanic and intrusive rocks and associated volcanogenic sedimentary rocks. It has been ascribed particular metallogenic significance as a locus for gold and base-metal accumulations (Gale and Ostry, 1984). In Saskatchewan, however, the junction has proved to be indistinctive, and the 'Kiseynew metallogene' is equally enigmatic (Parslow and Gaskarth, 1985; Parslow, 1986).

The Glennie Lake Domain is a volcano-sedimentary-plutonic complex characterized by a non-linear structural style. Supracrustal rocks and compositionally diverse intrusive rocks exhibit Lower Proterozoic ages similar to those obtained from the La Ronge and Flin Flon Domains. Older granulites, once surmised as possible Archean basement (Lewry, 1977, 1981), yield marginally older ages.

The Hanson Lake Block also shows a mixed volcanic and sedimentary sequence of supracrustal rocks, similar to that exposed in the Glennie Lake Domain. Here, however, definite Archean elements such as the charnockitic Sahli Granite and the Macmillan Point Granite, are geologically important (Macdonald, 1974; Macdonald and MacQuarrie, 1978). The Hanson Lake volcanic rocks also yielded an Archean age in early Rb-Sr dating work by Coleman (1970), but recently produced zircon dates give a Lower Proterozoic 1888 Ma for these rocks (Table 1).

Both domains have been suggested by Lewry (1981) to be microcontinents, 'suspect terrains', accreted to the La Ronge arc terrain to the northwest. In this respect, the northerly trending Tabernor Tectonic Zone of early mylonites, steep metamorphic gradients and late faulting is speculated to mark the locus of long-continued major transform movements occurring along a microplate boundary. Since the new dating (Bell and Macdonald, 1982; Bickford et al, 1986) from the Glennie Lake Domain fails to show evidence of Archean basement, this crustal unit is possibly better interpreted as a dismembered arc fragment than as a microcontinent.

THE LA RONGE-ROTTENSTONE MAGMATIC BELT

The La Ronge-Rottenstone Magmatic Belt has been identified as a major Cordilleran-type arc massif by Lewry et al (1981). It comprises tholeiitic to calc-alkaline metavolcanic rocks, plutons and volcanically derived clastic rocks in the La Ronge Domain and a major, 800-km-long, quartz dioritic to monzogranitic batholithic complex, the Wathaman Batholith, in the **Rottenstone Domain**. Migmatitic tonalitic gneisses

Table 1. Geological summary of the Southeastern Complex, northern Saskatchewan.

Subdivision	Interpretation	Major components	Zircon age in Ma
Flin Flon Domain	Volcano-plutonic arc	Missi Group Amisk Group Plutons	Younger than 1830 ¹ 1885 ¹ ± 1820 to 1880 ¹
Kiseynew Domain	Inter-arc basin	Kiseynew Gneisses (Nokomis = Amisk) (Sherridon = Missi)	
Glennie Lake Domain	Volcano-sedimentary-plutonic complex, possibly an arc fragment	Supracrustals Granite-gabbro plutons Older granite gneiss	1881 ² 1836 to 1859 ² 1893 ²
Hanson Lake Block	Volcano-sedimentary-plutonic complex, probably a basement microcontinent	Hanson Lake Group Sahli Granite	1888 ² 2500 ±, (1800 to 1900) ²

1. Flin Flon Domain data from R.R. MacQuarrie (unpublished).

2. Glennie Lake Domain and Hanson Lake Block data from Bickford et al, 1986. Bracketed data are lower concordia intercepts.

intervene between the Batholith and the La Ronge Domain and are transitional into the latter. They represent sediments probably for the greater part coeval with, and derived from, the La Ronge arc, and for the lesser part from the continental regime to the west. All units yield Lower Proterozoic zircon ages in the range 1830-1885 Ma (Table 2). Neodimium isotope studies point to the increasing presence of an Archean component passing northwestward from the La Ronge Domain (Chauvel et al, in press).

The La Ronge Domain has several subdivisions. The Central Metavolcanic Belt comprises predominant mafic to intermediate volcanic and volcanoclastic rocks with lesser felsic to intermediate material intruded by plutons. Plutons range in composition from gabbro to granite but are predominantly tonalitic to granodioritic. Volcanic geochemistry resembles that of subduction-generated oceanic arcs (Watters, 1986).

Metasediments on the southeast side in the MacLean Lake Belt are volcanogenic greywackes overlain by arkosic 'molasse' of the McLennan Group. They are apparently in thrust contact with, and over-ridden by, the Central Metavolcanic Belt. The MacLean Lake Belt may be a telescoped fore-arc basin. Greywackes and felsic to mafic volcanoclastic rocks typify the Crew Lake Belt to the northwest of the Central Metavolcanic Belt and may represent back-arc sediments.

To the northeast, the Central Metavolcanic Belt gives way to a terrain, possibly representative of deeper crust, which is

dominated by granodioritic to tonalitic plutons containing metavolcanic remnants. To the southwest, it becomes dismembered within a predominantly felsic gneiss complex, again probably representing deeper crustal material.

The Central Metavolcanic Belt is generally weakly deformed and metamorphosed to upper greenschist to lower amphibolite facies grade. Accordingly, primary volcanic features are often well preserved. Outward from this low-grade core, deformation intensity generally increases with the development of high-strain zones and more complex structures; metamorphic grade also increases to middle amphibolite facies, and greywacke metasediments to the southeast in the MacLean Lake Belt attain lowermost granulite facies.

The enigmatic **Peter Lake Domain**, lying between the Cree Lake Zone and the Wathaman Batholith, is characterized by ultramafic-mafic bodies of late Archean age, intrusive into older granite gneisses in the northeast part of the Domain. Most of the Domain also comprises younger, little-deformed granitoids, which are similar in character and age to those forming the Wathaman Batholith (ca. 1860 Ma). A Lower Proterozoic mafic suite has also been identified by age dating (Table 2). The Campbell River Group of supracrustals comprises predominant argillaceous metasediments, which are in part carbonaceous and sulphidic, together with psammites and hornblende-biotite schists and gneisses (Lewry et al, 1980). The relationship of the Campbell River Group to the

Table 2. Geological summary of the La Ronge-Rottenstone Magmatic Belt.

Subdivision	Interpretation	Major components	Zircon age in Ma
La Ronge Domain	Volcano-plutonic arc		
Central Metavolcanic Belt	High-level arc	Volcanics Plutons	1876 to 1882 ¹ 1834 to 1866 ¹
Northeastern Tonalitic Complex	Low-level arc	Volcanics Tonalite plutons	1837 ¹
Eastern La Ronge Domain	Fore-arc basin	MacLean Lake "greywackes" McLennan Group (= Sickie) "molasse"	
Western La Ronge Domain	Back-arc basin	Crew Lake "greywackes"	
Rottenstone Domain	Batholithic complex Back-arc basin	Wathaman Batholith Migmatitic tonalite gneisses	1830 to 1865 ^{1,2} 1863 ¹
Peter Lake Domain	Mafic and granitic intrusive complexes	Younger Granite (Wathaman) Younger Gabbro Mafic Intrusive Complex Campbell River Group Older Granite Gneiss	1860 ¹ 1865 ¹ 2538 ² ? 2556 to 2582 ¹

1. Data from Bickford et al (1986).

2. Data from Ray and Wanless (1980).

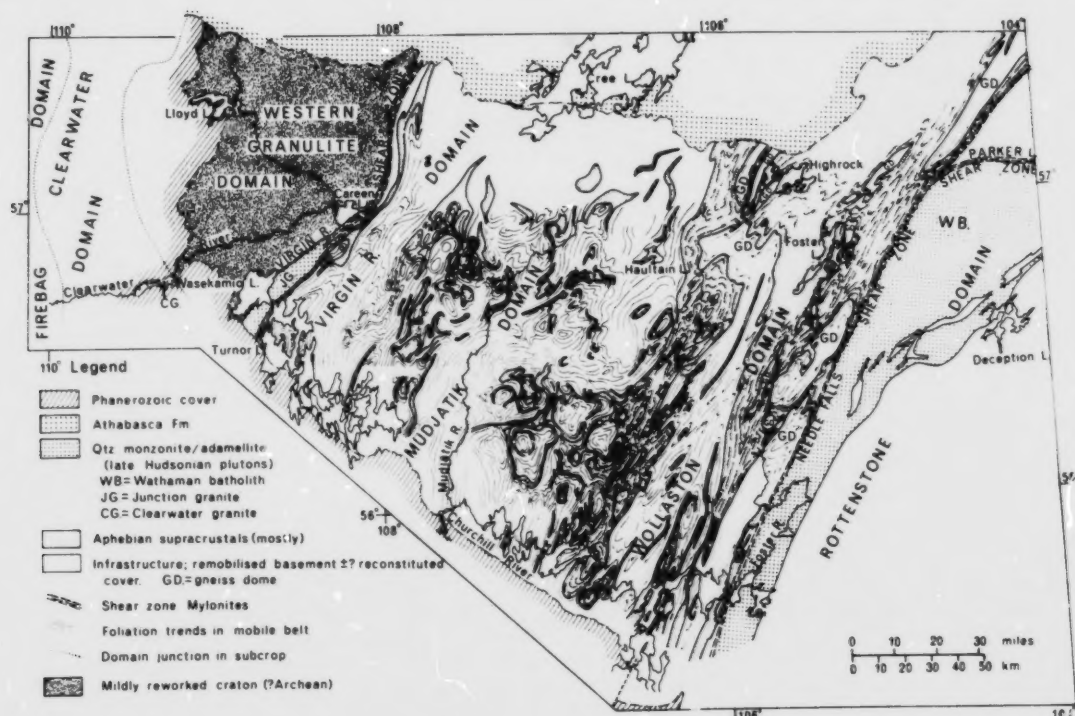


Figure 2. General geology of the southwestern Saskatchewan Shield; schematic cross-section in Figure 3 (after Lewry and Sibbald, 1980).

surrounding Archean ultramafic-mafic rocks is uncertain, as is the understanding of the Group's depositional setting.

THE CREE LAKE ENSIALIC MOBILE ZONE

The Cree Lake Ensialic Mobile Zone represents a region of major Hudsonian reworking (Table 3). It comprises granitoid

gneisses with subordinate shelf-type metasediments with some intermixed volcanics. Supracrustal rocks are most extensively developed in the **Wollaston Domain** (Fig. 2). They are presumed to be of Lower Proterozoic age and form a three- to four-kilometre-thick sequence with four main lithostratigraphic units (Lewry and Sibbald, 1980):

Table 3. Geological summary of the Cree Lake Ensialic Mobile Zone.

Subdivision	Interpretation	Major components	Zircon age in Ma
Wollaston Domain	Miogeoclinal shelf sediments and early rift clastics and volcanics overlying granitoid basement	Wollaston Group	?
Mudjatik Domain		Granite and granite gneisses	2494 ¹
Virgin River Domain			
Ennadai Group	Volcano-plutonic greenstone belt	Volcanics Plutons	2683 ²

1. Data from Ray and Wanless (1980).

2. Data from Bickford and Van Schmus (1985).

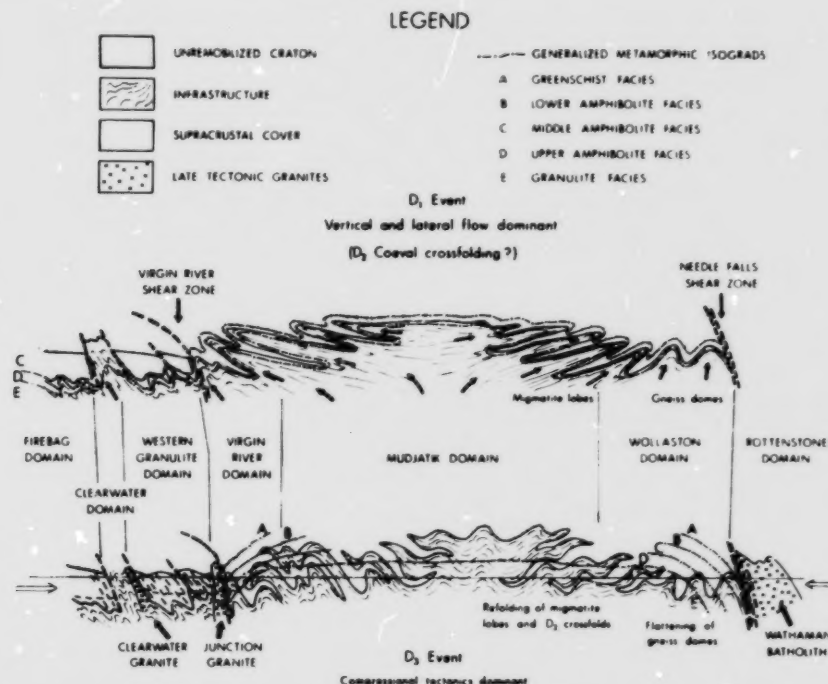


Figure 3. Schematic cross-section showing the thermotectonic evolution of the southwestern Saskatchewan Shield and the relationships between the different domains (after Lewry and Sibbald, 1980).

- 1) a basal, coarse, mature clastic unit of quartzites and quartz-pebble conglomerates which is of variable thickness and is most extensively developed along the eastern margin of the mobile zone, where it is underlain by immature arkose and mafic volcanic rocks possibly representing an early rift sequence;
- 2) a dominantly pelitic unit which is locally graphitic; to the west, the unit is interlayered with mafic to ultramafic volcanic rocks and iron formation;
- 3) a thick arkosic unit containing calc-silicates, marbles, and pelitic subunits; and
- 4) an uppermost unit characterized by quartzites and possible mafic volcanic and intrusive rocks (amphibolites); this, the Hidden Bay assemblage, is developed only in the Wollaston Lake area.

The Zone is interpreted as a region of miogeoclinal Lower Proterozoic sedimentation on a granitoid Archean basement which, at least in the area south of the Athabasca Basin, has undergone intense Hudsonian orogenesis — high-grade (amphibolite to granulite facies) metamorphism and ductile interaction between granitoid basement and cover. In the core of this Zone, represented by the **Mudjatik Domain**, Lewry and Sibbald (1980) suggested that during orogenesis migmatite nappe lobes formed, whereas in the margins, formed by the **Wollaston** and **Virgin River Domains**, mantled gneiss domes developed (Fig. 3). The mobile infrastructure appears to plunge gently to the northeast, so that north of the Athabasca Basin, Lower Proterozoic supracrustal rocks of the Many Islands Belt (probably equivalent to the Hurwitz Group [Munday, 1973]) and Archean basement, which comprises in part the southernmost extension of the Kaminak Greenstone

Belt, were little-disturbed by these events. However, the area is poorly documented.

The Mobile Zone is bounded by major shear zones, corresponding with steep drops in metamorphic grade from granulite to lower amphibolite facies. The Needle Falls Shear Zone marks the Zone's southeastern boundary, and the Virgin River-Black Lake Shear Zone its northwestern limit.

THE WESTERN CRATON

The **Western Craton**, recently renamed the **Amer Lake Zone** by Lewry et al (1985) and more recently further subdivided into the **Keewatin** and **Thelon Zones** by Lewry and Collerson (unpublished manuscript), extends from the Virgin River — Black Lake Shear Zone to the McDonald Fault and Thelon Front.

In Saskatchewan, it consists mainly of Archean basement, Lower Proterozoic granite plutons and migmatites, and scattered Aphebian and, possibly, older supracrustal remnants. North of the Athabasca Basin, in particular, where systematic lithostructural subdivisions have not been recognized as in the south, the geology of the Craton is extremely complex and poorly understood. However, some general comments are offered later.

South of the Athabasca Basin, the Western Craton comprises the **Western Granulite** and essentially unexposed **Firebag Domains** of retrogressed granulite facies rocks separated from one another by the linear **Clearwater Domain** of lower grade, amphibolite facies rocks (Lewry and Sibbald, 1977) (Table 4).

The Western Granulite and Firebag Domains are characterized by sedimentary, possibly metavolcanic, and intrusive

Table 4. Geological summary of the Western Craton (Amer Lake Zone) south of the Athabasca Basin.

Subdivision	Interpretation	Major components	Zircon age in Ma
Western Granulite Domain	Weakly reworked craton	Retrogressed granulites	Older than 2290 ¹
		Anorthosite complex	2000 ? ¹
		Junction Granite	1820 ¹ (1890; cores)
Firebag Domain	Weakly reworked craton	Retrogressed granulites	
Clearwater Domain	Strongly reworked	Granite and granite gneisses Clearwater Granite (= Junction Granite)	

1. Data from Bickford et al (1986).

components occurring as blue-quartz quartzofeldspathic, pelitic and hornblendic gneisses, charnockites and relatively rare anorthositic and noritic rocks. The Clearwater Domain, in-so-far as it is exposed, comprises predominant granitoid gneisses resembling those forming the infrastructure of the Cree Lake Ensialic Mobile Zone and a major granite pluton, the Clearwater Granite. A similar granite (the Junction Granite) intrudes the Western Granulite Domain along its southeastern boundary and incorporates early mylonites of the Virgin River Shear Zone.

Zircon age-dating work suggests a minimum age of 2290 Ma for the granulites, a possible age of 2000 Ma for the anorthositic complex and an age of 1820 to 1890 Ma for the Junction and equivalent Clearwater Granites (Bickford et al, 1985).

North of the Athabasca Basin (Table 5), similar predominantly retrogressed granulite facies domains and blocks are recognized — the **Tantato Domain**, the **Nevins Lake Block** and the **Nolan Block**. Intervening areas, again

Table 5. Geological summary of the Western Craton (Amer Lake Zone) north of the Athabasca Basin.

Archean elements	Lower Proterozoic supracrustal rocks	Lower Proterozoic plutons and gneissic terrains	Zircon age or Rb-Sr isochron age
Tantato Domain			?
Nolan Block			2581 to 2639 ¹
Nevins Lake Block			2630 ¹ 2315 ¹
Lodge Bay Granite			3014 to 3072 ¹
Foot Bay Gneiss			2513 ²
	Thluicho Lake Group		
	Waugh Lake Group		
	Murmac Bay Group		
		Donaldson Lake Gneiss	2179 ²
		North Shore Granites	2327 to 2356 ¹ , 1994 ¹
		Gunnar Granite	2181 ¹
		Train Lake Domain	1950 ³

1. Data from Van Schmus et al (1986).

2. Data from Tremblay et al (1981).

3. Rb-Sr data from Bell and Blenkinsop (1984).

characterized by lower metamorphic grade, are diverse in character and form granitic migmatite complexes (**Train Lake Domain**), Lower Proterozoic (?) supracrustal complexes invaded by granite plutons (Goldfields area) and zones of intense tectonism marked by extensive mylonite development and strong retrogression (Beaverlodge area and Grease River Shear Zone). The most recent zircon and Rb-Sr dating of the granulites and surviving older components of the intervening zones yields ages ranging from 2500 to 3000+ Ma. Plutons intrusive into the presumed Lower Proterozoic Murmac Bay Group in the Goldfields area are dated at about 2000 and 2340 Ma, and the Train Lake migmatite complex at around 2000 Ma.

Lower Proterozoic orogenesis has apparently influenced the Western Craton irregularly, leaving relatively untouched cratonic nuclei which are generally surrounded by restricted (often), linear zones of thermotectonism. This style contrasts markedly with the comparatively homogeneous tectonic and thermal character of the Cree Lake Ensialic Mobile Zone. More than one orogenic episode likely occurred between 2350 and 1900 Ma. Thus, by the time the Southeastern Complex began to be assembled, the Western Craton had largely evolved.

The general structural character of the Craton is clearly seen on regional aeromagnetic maps. The cratonic nuclei conform with areas of high magnetic amplitude and intensity, the intervening zones of Lower Proterozoic thermotectonic reworking with areas of relatively lower magnetic amplitude and intensity. A major negative gravity feature is also noted to coincide with the Clearwater and Tantato reworking zones. It extends far into the Northwest Territories and into southeastern British Columbia. Darnley (1981) has pointed out that the gravity anomaly is marked by a belt of uranium enrichment, the Athabasca Axis, apparent from regional radiometric surveys and other work. The association between abnormally radioactive granitoids and negative gravity anomalies is well documented, for example in the Nova Scotia Batholith and in the Cornubian Batholith of southwest England — bodies which also contain tin and tungsten mineralization. Whether radioelement-enriched granites, such as the Clearwater and Junction Granites and granitoids north of Lake Athabasca, within the negative gravity belt in Saskatchewan have any potential for these elements is currently unknown.

THE ATHABASCA BASIN AND ASSOCIATED URANIUM MINERALIZATION

The Athabasca Group unconformably overlies the crystalline basement and is a fluvial and marine clastic sequence deposited in Paleohelikian times (about 1450 Ma). It is separated from the basement by a paleoweathered zone which is of lateritic character and which is typically around 50 m thick.

The Group covers an area of approximately 100,000 km², is up to about 1400 m thick, and comprises four marine transgressive sequences and one regressive fluvial wedge (Manitou Falls Formation) (Ramaekers, 1981; see Figs. 4 and 5). It forms a fining-upward sequence of hematized quartz sandstones with conglomerates at the base and minor mudstones. These coarse clastics are capped by dolomites of the Carswell Formation. Tuffs and phosphatic units characterize the middle of the succession (Upper Wolverine

Point Formation). The Group is cut by a swarm of diabase dykes yielding Rb-Sr ages of 1310 and 1160 Ma (Armstrong and Ramaekers, 1985).

To Saskatchewan, the Athabasca Basin is of paramount importance as the host to the richest uranium deposits in the world. In 1985, three mines at Key Lake, Cluff Lake and Rabbit Lake-Collins Bay (Fig. 6) produced some 5.9 million kilograms of uranium valued at \$456 million (Table 6). Low-cost reserves are estimated at 350,000 tonnes uranium metal (ten per cent of the world's total reserves) of which 148,000 tonnes are contained within the huge, rich (12 per cent U) Cigar Lake deposit.

The main geological characteristics of these deposits are well defined (Sibbald, 1985; see Fig. 7):

- 1) proximity to the sub-Athabasca unconformity (above or below);
- 2) proximity to graphitic basement rocks;
- 3) structural controls:
 - a) post-Athabasca Group faulting (often thrust faulting as at Rabbit Lake and Collins Bay B-Zone),
 - b) topographic ridges in the basement, and
 - c) solution collapse structures in the basement (carbonates) and in the Athabasca Group (quartz sandstones);
- 4) extensive alteration envelopes, marked typically by illitization, but also by Mg-chloritization, Mg-tourmalinization, silicification, dolomitization and hematization;
- 5) high grades of mineralization ranging from an extremely high 12 per cent U at Cigar Lake to a respectable 0.4 per cent at Collins Bay;
- 6) primary uranium ore minerals, pitchblende and coffinite;
- 7) age of initial mineralization (ca. 1300 Ma) which postdates deposition of the Athabasca Group (ca. 1450 Ma); and
- 8) complex mineralogy and geochemistry (U + Ni, Co, As, Cu, Mo, Pb, Zn, Fe, V, Y, possibly REE although appropriate data is lacking, Ag, and rarely Au and PGEs).

The degree to which the associated elements are concentrated with uranium is variable. The Rabbit Lake and Eagle Point deposits contain little other than uranium. Nickel and arsenic are significant in many deposits (for example Key Lake and Cigar Lake). Gold is now to be recovered from radioactive tailings produced during processing of the Cluff Lake D deposit. Vanadium is concentrated in ores from the historic Fish Hook Bay Mine south of Beaverlodge, and zones of mineralization rich in Y and REEs have been reported to occur in the Basin.

In the light of these observations, the potential for economic concentrations of these associated elements within and immediately underlying the Basin should be considered.

The diagenetic-hydrothermal model of Hoeve and Sibbald (1978) appears to provide an acceptable mechanism for deposit genesis. The model invokes the interaction of the crystalline basement and the Athabasca Group through the mixing of

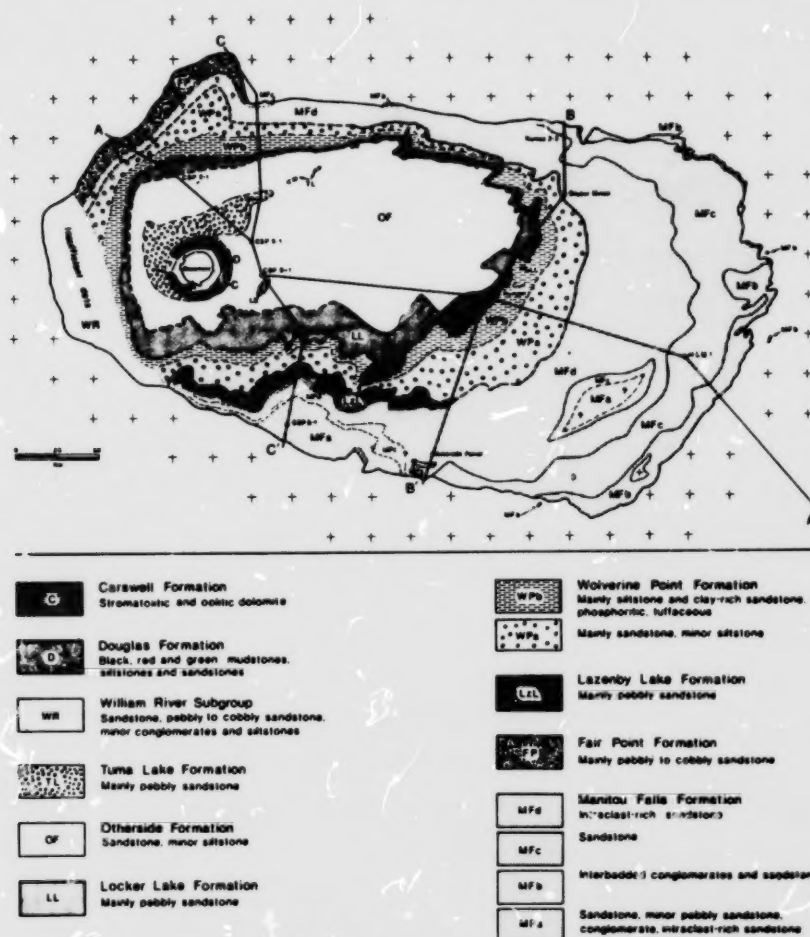


Figure 4. Geological map of the Athabasca Basin. Locations of cross-sections in Figure 5 also shown (after Ramaekers, 1981).

fluids of contrasting chemistry. Oxidized formational brines of the Athabasca Group aquifer enter the basement along fractures, react with the wallrocks, and re-emerge with reduced character. At or in close proximity to the sub-Athabasca unconformity, the now reduced fluids mix with the oxidized aquifer creating a dynamic but essentially stationary redox front around a reductant plume.

Given this scenario, metals in solution in the oxidized aquifer have two potential locations for deposition:

- 1) at the points of inflow to the basement through reaction with wallrocks; and
- 2) at the redox front surrounding the reductant plume.

Deposits of the first type (for example Eagle Point, and Cluff Lake N- and Claude Zones) form vein-type systems in the crystalline basement in contrast to deposits of the second type, which are characterized by pods of extremely high-grade ore at or close to the sub-Athabasca unconformity.

For mineralization to occur, metal-charged fluids must circulate effectively. Convection within the one-kilometre-

thick, vertically monotonous, fluvial clastic wedge formed by the Manitou Falls Formation in the eastern Basin provides a mechanism, with convection cells focused over hot spots in the basement provided by relatively more conductive graphitic rocks. However, for convection to occur, theoretical calculations indicate high geothermal gradients of greater than 35 to 40 °C/km should prevail (Hoeve and Quirt, 1984). Such conditions might be realized during periods of elevated regional heat flow accompanying diabase-dike emplacement. Age dating of the deposits suggests more than one formative event between 1300 and 1000 Ma ago. This time-span correlates with the limited data available from age dating of the diabase dykes.

GOLD MINERALIZATION

Advocates of gold exploration in Lower Proterozoic environments face a significant hurdle, for most gold production in the world has been from the Witwatersrand Basin, and to a lesser extent from Archean greenstone belts and the Mesozoic and younger volcanic and intrusive rocks rimming the Pacific Ocean; only a small contribution has come from Lower Proterozoic rocks. Additionally, the Lower

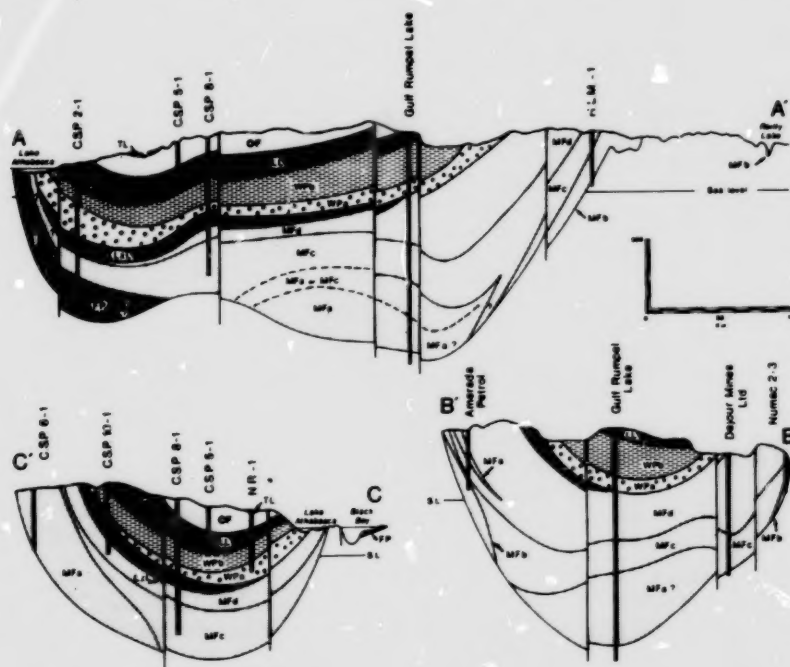


Figure 5. Cross-sections through the Athabasca Basin. Location shown in Figure 4 (after Ramaekers, 1981).

Proterozoic contribution has been in great part from non-greenstone environments, such as the 34 million ounces or more from the Homestake Mine in South Dakota (Nelson, 1986) in a greywacke basin.

Do these figures mean that Lower Proterozoic volcanic environments have lesser potential for economically viable gold occurrences than those in the Archean? Or do they mean simply that Lower Proterozoic volcanic environments form a smaller volume of the earth's crust than their Archean counterparts, and/or have not been explored to the same degree?

In the Canadian context, comparisons of gold exploration expenditures, recoverable gold in potentially economic discoveries and exploration costs per ounce in the Archean environments of Quebec and Ontario, and in the Lower Proterozoic environment of Saskatchewan are illustrated in Table 7.

The figures seem to indicate that the gold-exploration dollar spent in Saskatchewan is as effective as the one spent in Quebec or Ontario, and that Saskatchewan is relatively unexplored.

Historically, Saskatchewan has not been a significant gold producer. Over 90 per cent of gold output has come as a by-product of base-metal production from Hudson Bay Mining and Smelting's Flin Flon base-metal operations. The largest primary gold producer was the Box Mine at Goldfields which produced some 64,000 ounces between 1939 and 1942. Today, several deposits are at an advanced stage of exploration (Table 8), and the 30,000 oz/year Star Lake Mill started up in late-1986.

The current gold exploration boom in northern Saskatchewan, valued at around \$20 million in 1986, has focused on known gold showings and their immediate surroundings in the Central Metavolcanic Belt of the La Ronge Domain particularly in the Sulphide Lake, Star Lake and Waddy-Tower Lakes areas. Other major auriferous areas are:

- 1) Laonil Lake area (Seabee deposit) in the Glennie Lake Domain,
- 2) Flin Flon-Amisk Lake area in the Flin Flon Domain,
- 3) Thompson Island area in the Tantato Domain, and
- 4) Goldfields area, south of Uranium City.

Most gold occurrences in the Central Metavolcanic Belt are structurally controlled and of quartz-vein type. Host rocks

Table 6. Selected statistical figures for uranium production in Saskatchewan, 1985.

Production (million kg U)	5.9
Value (million \$)	456
Percentage of Canadian production	55
Percentage of world production	17
Exploration expenditure (million \$)	19.5
Low-cost reserves (tonnes U) (less than \$150/kg)	350,000
Percentage of Canadian reserves	80
Percentage of free-world reserves	10

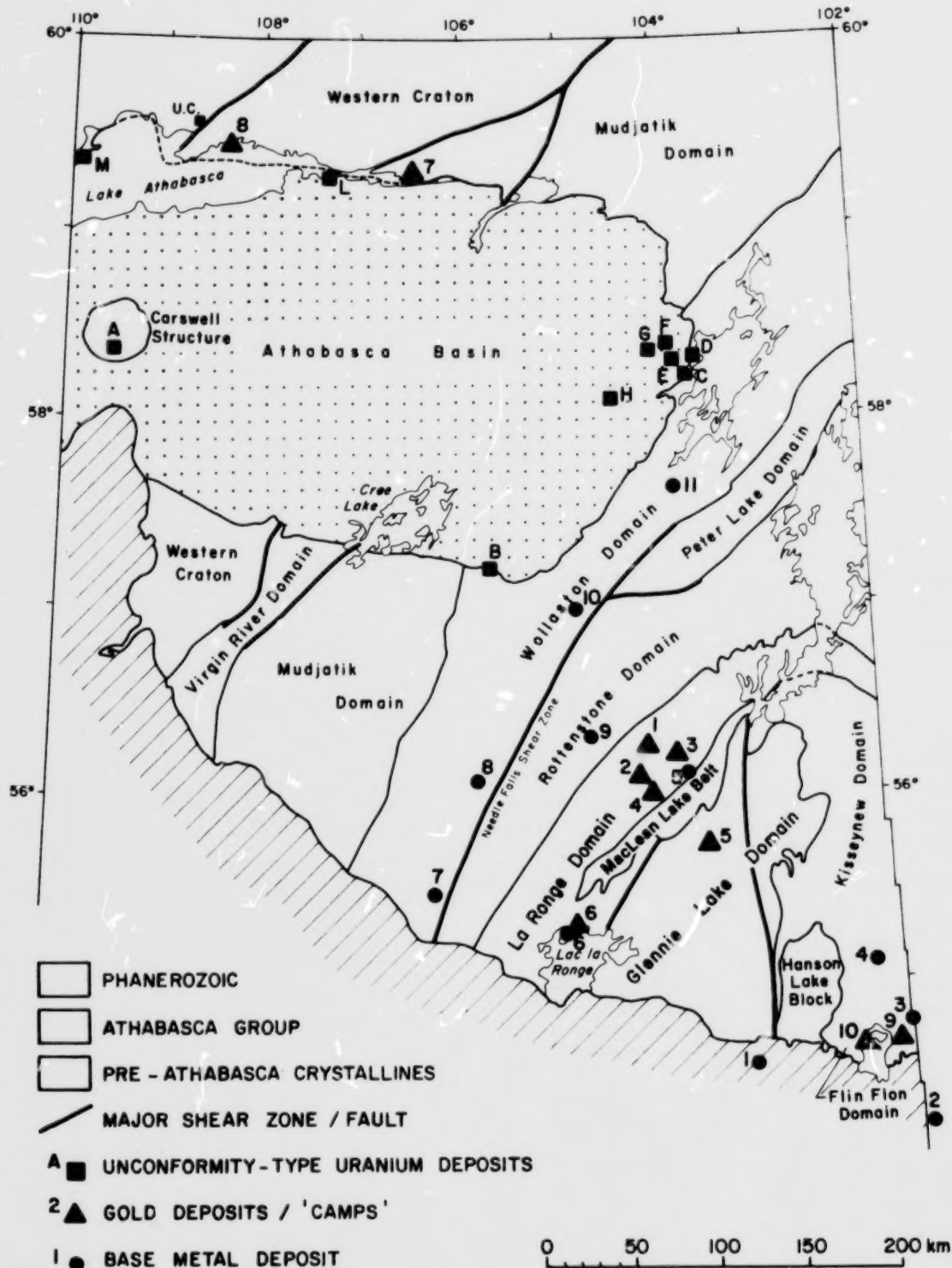


Figure 6. Locations of major unconformity-type uranium deposits, major gold deposits and gold 'camps', and base-metal deposits referred to in text. *Uranium deposits:* A, Cluff Lake; B, Key Lake; C, Rabbit Lake; D, Collins Bay A, B Zones and Eagle Point; E, McClean Lake; F, Dawn Lake; G, Midwest; H, Cigar Lake. *Gold deposits and gold 'camps':* 1, Tower Lake; 2, Rod-Mallard Zones; 3, Waddy Lake; 4, Star Lake; 5, Laonil Lake (Seabee); 6, Sulphide-Preview Lakes; 7, Thompson Island; 8, Goldfields; 9, Amisk Lake; 10, Flin Flon. *Base-metal deposits:* 1 Bigstone Lake (Cu-Zn); 2, Namew Lake (Ni); 3, Flin Flon (Cu-Zn); 4, Schott's Lake (Cu-Zn); 5, Brabant Lake (Zn); 6, Anglo Rouyn (Cu-Ag, Au); 7, Duddridge Lake (U-Cu); 8, Siro Lake (Zn-Pb); 9, Rottenstone Lake (Ni-Cu-PGE); 10, Janice Lake (Cu-Ag, Au); 11, George Lake (Zn-Pb).

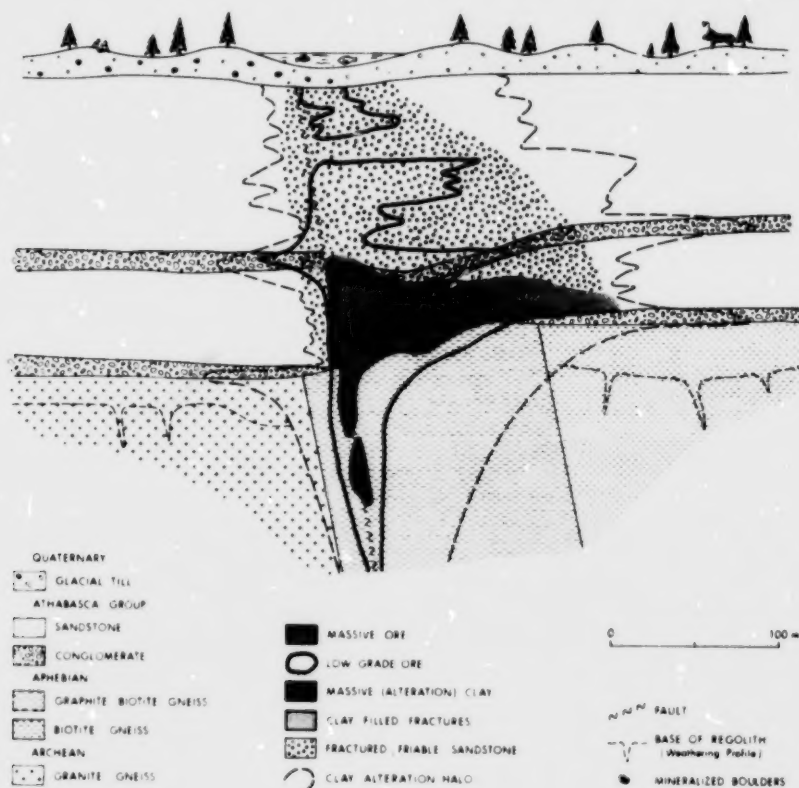


Figure 7. Idealized "model" Athabasca Basin unconformity-type uranium deposit.

include both supracrustal rocks (metavolcanic and metasedimentary) and plutons of different compositions and age. Controlling structures may be high-temperature shear zones essentially contemporaneous with the main thermotectonic events (Star Lake 21 Zone, Pap Zones and also the Seabee deposit in the Glennie Lake Domain) and late, low-temperature and retrograde, regional fault structures such as the Byers Lake Fault (Pat Zone at Tower Lake, Weedy Lake). Stratiform gold occurrences are most extensive in the Sulphide Lake area, where gold is closely related to the presence of black, carbonaceous, sulphidic meta-argillite layers (lean iron formation) developed during an hiatus in intermediate-felsic volcanism and sedimentation (Sibbald, 1984).

The Flin Flon-Amisk Lake area is characterized by a spectrum of gold-occurrence types of pre- and syn- to late-tectonic age (Pearson et al, 1986).

Early-generation gold occurrences in the West Channel of Amisk Lake are typified by quartz-vein systems surrounded by extensive alteration haloes of carbonate, sericite and silica. They are present in supracrustal rocks and felsic intrusives in both subvolcanic and structural settings. Formation in a near-surface, possibly epithermal environment (as suggested for the Laurel Lake deposit [see Walker and McDougall, this volume]) is indicated.

By contrast, the Flin Flon area is characterized by structurally controlled deposits in both supracrustal rocks and invading plutons of all ages. These have been related to an anorogenic porphyry system (Pearson et al, 1986).

North of Lake Athabasca, the Thompson Island area is typified by metamorphosed gold-bearing quartz veins occupying northwest-trending dilational fractures. Host rocks are retrogressed-granulite-facies, garnetiferous

Table 7. Comparison of gold exploration costs (in millions of dollars using the value of the Canadian dollar in 1985), recoverable reserves (in millions of ounces) and exploration costs (in Canadian dollars, 1985) per ounce in Saskatchewan, Quebec and Ontario.

		Sask.	Que.	Ont.
Gold exploration expenditure	1946-74	10	186	183
	1975-84	19	305	245
	Total(1946-84)	29	491	428
	1984-86	25		
Recoverable gold in discoveries		1.5	21	28 ¹
Exploration cost per ounce		19	23	15 ²

1. 22 million ounces estimated to be contained by the Hemlo deposit.

2. Excluding Hemlo, this figure escalates enormously to ca. \$70/oz.

quartzofeldspathic gneisses and hypersthene-bearing metabasic rocks (norites). Presumably, gold was mobilized from the country rocks by retrogressive metamorphic fluids which at a late stage deposited the gold-quartz veins.

At Goldfields, gold mineralization is hosted by discrete Lower Proterozoic (2350 Ma) granitic bodies cut by quartz-vein stockworks. Three major deposits are recognized in the Box Mine (the only producer) and the Athona and Frontier prospects which underwent underground development. In the Box and Athona, probable reserves amount to some 3.5 million tons grading 0.07 ounces per ton gold, and 10 to 15 million tons of lower grade possible reserves at the Box. The mined grade at the Box was around 0.045 ounces per ton gold (Christie, 1953).

The host granites are metasomatically derived from feldspathization (potassium metasomatism) of feldspathic quartzites. The quartz-vein stockworks developed during retrograde metamorphism (possibly at about 2000 Ma) (Van Schmus et al, 1986) marked by regional chloritization and in the Box and Athona Granites by albitization (Sibbald and Jiricka, 1986). Whether gold mineralization accompanied potassium metasomatism and was remobilized and concentrated in the later quartz-veining event, or whether it was introduced during the single later event, is uncertain.

BASE-METAL MINERALIZATION

The distribution of different base-metal deposits, much as that of gold, clearly reflects the distinction in crustal character between the northwestern and southeastern segments of the Saskatchewan Shield (Coombe, 1979). In the northwest, the Lower Proterozoic miogeoclinal Wollaston Group, which characterizes the Wollaston Domain, is host to essentially sedimentogenic deposits such as:

- 1) quartzite-hosted Zn-Pb deposits at George Lake (Karup-Moller and Brummer, 1970) and Sito Lake (Potter, 1980);
- 2) arkosic conglomerate and arkose-hosted Cu $\pm$ Pb, Ag, Au mineralization (red-bed copper deposits) in the Janice Lake area (Rath and Morton, 1969; Scott, 1973); and

- 3) arkose-hosted U-Cu $\pm$ Ni, Co, As, Se, Pb, Ag, Au, Mo and V mineralization at Duddridge Lake (Bretzlaff, 1976; Coombe, 1978).

In contrast, eugeoclinal volcano-plutonic arc and interarc domains to the southeast contain essentially volcanogenic deposits such as:

- 1) proximal, volcanic-hosted Cu, Cu-Zn, Zn and Pb-Zn deposits epitomised by the Flin Flon (Koo and Mossman, 1975), and Bigstone Lake massive-sulphide Cu-Zn deposits; and
- 2) distal, sediment-hosted deposits characterized by the Anglo Rouyn Cu $\pm$ Ag, Au deposit (Forsythe, 1972), Schotts Lake Cu-Zn deposit (Pearson, 1986) and Brabant Lake Zn deposit (Johnston, 1973).

Mafic and ultramafic rocks of various origins sporadically hosting nickel-copper mineralization occur in both Archean and Lower Proterozoic environments. To date, within Saskatchewan, only the small Rottenstone Ni-Cu deposit mined between 1965 and 1968 has proved economic, largely on account of its extraordinarily rich PGE, Au and Ag contents. The ore, confined within a sill-like harzburgite-orthopyroxenite body which occurs as an isolated inclusion within trondjhemitic migmatite (Gilboy, 1982), comprised disseminated and net-textured sulphides, mainly pyrrhotite-pentlandite (or violarite) and chalcopyrite. Minor quantities of carbonate, magnetite, chromite, pyrite and sperrylite were associated (Richards and Robinson, 1966). Ore reserves and grades quoted by the Northern Miner (April 15, 1965) were 50,000 to 60,000 tons of two per cent Ni, two per cent Cu, 0.22 ounces per ton Pt and 0.15 ounces per ton Pd.

Major economic magmatogenic nickel-copper deposits have proved elusive in Saskatchewan. However, a short distance across the Saskatchewan-Manitoba border, the Lynn Lake deposit in the strike extension of the La Ronge Domain and the recently discovered Namew Lake deposit in the Flin Flon Domain serve as reminders of a perhaps unrealized potential in the province.

REFERENCES

Table 8. Saskatchewan gold discoveries of potential economic viability.

Deposit	Oz. gold x 1000
Seabee	352
Komis	177
Tower East	72
Wedge	95
Weedy	117
Star Lake	115
Mahogany (Mallard/Rod)	559
	<u>1,486</u>

- Armstrong, R.L., and P. Ramaekers, 1985, Sr isotopic study of Helikian sediments and diabase dikes in the Athabasca Basin, northern Saskatchewan: *Canadian Journal of Earth Sciences*, v. 22, p. 399-407.
- Ashton, K.E., K.J. Wheatley, D. Moser, D. Paul, and K.H. Wilcox 1986, The Kiseynew Gneisses of Saskatchewan: update, in R. Macdonald, T.I.I. Sibbald and D.F. Paterson, eds., *Summary of Investigations 1986*, Saskatchewan Geological Survey: Saskatchewan Energy and Mines Miscellaneous Report 86-4, p. 145-148.
- Bailes, A.H., and W.D. McRitchie, 1978, The transition from low to high grade metamorphism in the Kiseynew sedimentary gneiss belt, Manitoba, in J.A. Frazer and W.W. Heywood, eds., *Metamorphism in the Canadian Shield*: Geological Survey of Canada Paper 78-10, p. 155-177.

- Bateman, J.D., and J.M. Harrison, 1946, Sherridon, Manitoba: Geological Survey of Canada Map 862A with descriptive notes.
- Bell, K., and J. Blenkinsop, 1984, Saskatchewan Shield Rb-Sr geochronology, in R. Macdonald and T.I.I. Sibbald, eds., Summary of Investigations 1984, Saskatchewan Geological Survey: Saskatchewan Energy and Mines Miscellaneous Report 84-4, p. 122.
- Bell, K., and R. Macdonald, 1982, Geochronological calibration of the Precambrian Shield in Saskatchewan, in R. Macdonald, T.I.I. Sibbald, D.F. Paterson, P. Gulio and J.V. Buller, eds., Summary of Investigations 1982, Saskatchewan Geological Survey: Saskatchewan Energy and Mines Miscellaneous Report 82-4, p. 17-22.
- Bickford, M.E., and W.R. van Schmus, 1985, Preliminary U-Pb age data for the Trans-Hudson Orogen in northern Saskatchewan: new and revised results, in R. Macdonald, T.I.I. Sibbald and D.F. Paterson, eds., Summary of Investigations 1985, Saskatchewan Geological Survey: Saskatchewan Energy and Mines Miscellaneous Report 85-4, p. 63-66.
- Bickford, M.E., W.R. van Schmus, R. Macdonald, J.F. Lewry, and J.G. Pearson, 1986, U-Pb zircon geochronology project for the Trans-Hudson Orogen: current sampling and recent results, in R. Macdonald, T.I.I. Sibbald and D.F. Paterson, eds., Summary of Investigations 1986, Saskatchewan Geological Survey: Saskatchewan Energy and Mines Miscellaneous Report 86-4, p. 101-107.
- Bretzlaff, R.E., 1976, Genesis of uranium mineralization at Duddridge Lake, Saskatchewan: unpublished B. Sc. thesis, Carleton University, Ottawa.
- Byers, A.R., and C.D.A. Dahlstrom, 1954, Geology and mineral deposits of the Amisk-Wildnest Lakes area, Saskatchewan: Saskatchewan Department of Mineral Resources Report 14, 177 p.
- Camfield, P.A., and D.I. Gough, 1977, A possible Proterozoic plate boundary in North America: Canadian Journal of Earth Sciences, v. 14, p. 1229-1238.
- Chauvel, C., N.T. Arndt, W. Todt, S. Kielenzuck, and A. Thom, in press, Formation of Canadian 1.9 Ga old continental crust: (1) Nd isotopic data: Canadian Journal of Earth Sciences.
- Christie, A.M., 1953, Goldfields - Martin Lake map-area, Saskatchewan: Geological Survey Canada Memoir 269, 126 p.
- Coleman, L.C., 1970, Rb/Sr isochrons for some Precambrian rocks in the Hanson Lake area, Saskatchewan: Canadian Journal of Earth Sciences, v. 7, p. 338-345.
- Coombe, W.C., 1978, Wollaston base metals project, Duddridge Lake to Myers Lake area, in J.E. Christopher and R. Macdonald, eds., Summary of Investigations 1978, Saskatchewan Geological Survey: Saskatchewan Department of Mineral Resources Miscellaneous Report 78-10, p. 98-108.
- Coombe, W.C., 1979, Mineral deposits and regional metallogeny, southeastern Shield, in J.E. Christopher and R. Macdonald, eds., Summary of Investigations 1979, Saskatchewan Geological Survey: Saskatchewan Department of Mineral Resources Miscellaneous Report 79-10, p. 120-133.
- Darnley, A.G., 1981, The relationship between uranium distribution and some major crustal features in Canada: Mineralogical Magazine, v. 44, p. 425-436.
- Forsythe, L.H., 1972, Anglo-Rouyn copper mine, Ore Bay, Lac La Ronge, Saskatchewan: Geological Society of America Bulletin, v. 83, p. 3405-3413.
- Gale, G.H., and G. Ostry, 1984, GS-18: Stratabound gold mineralization in the Kisseynew gneiss terrain, in Report of Field Activities, 1984, Manitoba Department of Energy and Mines, p. 73-80.
- Gilboy, C.F., 1982, Geology of an area around Rottenstone and Dobbin Lakes: Saskatchewan Energy and Mines Report 193, 67 p.
- Hills, F.A., and R.L. Armstrong, 1974, Geochronology of Precambrian rocks in the Laramie Range and implications for the tectonic framework of Precambrian southern Wyoming: Precambrian Research, v. 1, p. 1453-1467.
- Hoeve, J., and T.I.I. Sibbald, 1978, On the genesis of Rabbit Lake and other unconformity-type uranium deposits in northern Saskatchewan, Canada: Economic Geology, v. 73, p. 1450-1473.
- Hoeve, J., and D. Quirt, 1984, Mineralization and host rock alteration in relation to clay mineral diagenesis and evolution of the Middle-Proterozoic Athabasca Basin, northern Saskatchewan, Canada: Saskatchewan Research Council Publication R-855-2-B-84, 187 p.
- Johnston, W.G.Q., 1973, Base metal geochemistry, Brabant Lake area, Saskatchewan: Saskatchewan Department of Mineral Resources Report 148, 27 p.
- Karlstrom, K.E., A.J. Flurkey, and R.S. Houston, 1983, Stratigraphy and depositional setting of the Proterozoic Snowy Pass Supergroup, southeastern Wyoming: record of an early Proterozoic Atlantic-type cratonic margin: Geological Society of America Bulletin, v. 94, p. 1257-1274.
- Karup-Moller, S., and J.J. Brummer, 1970, The George Lake zinc deposit, Wollaston Lake area, northeastern Saskatchewan: Economic Geology, v. 65, p. 862-874.
- Koo, J., and D.J. Mossman, 1975, Evaluation of primary and secondary geological processes at the Flin Flon Cu-Zn deposit, Manitoba and Saskatchewan, Canada, using factor-vector analysis of ore geochemistry: Chemical Geology, v. 16, p. 1-14.
- Lewry, J.F., 1977, The geology of the Glennie Lake area: Saskatchewan Department of Mineral Resources Report 143, 59 p.

- Lewry, J.F., 1981, Lower Proterozoic arc-microcontinent collisional tectonics in the western Churchill Province: *Nature*, v. 294, no. 5836, p. 69-72.
- Lewry, J.F., and K.D. Collerson, unpublished manuscript, The early Proterozoic Trans-Hudson Orogen and contiguous elements of the North American Craton: lithotectonic subdivision and terrane analysis.
- Lewry, J.F., and T.I.I. Sibbald, 1977, Variation in lithology and tectonometamorphic relationships in the Precambrian basement of northern Saskatchewan: *Canadian Journal of Earth Sciences*, v. 14, p. 1453-1467.
- Lewry, J.F., and T.I.I. Sibbald, 1980, Thermotectonic evolution of the Churchill Province in northern Saskatchewan: *Tectonophysics*, v. 68, p. 45-82.
- Lewry, J.F., K. Roberts, and C.J. Rees, 1980, Geology of the area around Spalding Lake: Saskatchewan Department of Mineral Resources Report 199, 18 p.
- Lewry, J.F., T.I.I. Sibbald and D.C.P. Schledewitz, 1985, Variation in character of Archean rocks in the western Churchill Province and its significance, in L.D. Ayres, P.C. Thurston, K.D. Card and W. Weber, eds., *Evolution of Archean Supracrustal Sequences: Geological Association of Canada Special Paper 28*, p. 239-261.
- Lewry, J.F., M.R. Stauffer, and S. Fumerton, 1981, A Cordilleran-type batholithic belt in the Churchill Province in northern Saskatchewan: *Precambrian Research*, v. 14, p. 277-313.
- Macdonald, R., 1974, Pelican Narrows (west) area: reconnaissance geological survey of 63M-2(W), in *Summary Report of Field Investigations by the Saskatchewan Geological Survey, 1974: Saskatchewan Department of Mineral Resources*, p. 30-37.
- Macdonald, R., and R.R. MacQuarrie, 1978, Geological re-investigation mapping, Jan Lake area (part of NTS area 63M), in J.E. Christopher and R. Macdonald, eds., *Summary of Investigations 1978, Saskatchewan Geological Survey: Saskatchewan Department of Mineral Resources Miscellaneous Report 78-10*, p. 16-24.
- Munday, R.J.C., 1973, The geology of the Dutton Lake area (east half), Saskatchewan: Saskatchewan Department of Mineral Resources Report 155, 22 p.
- Nelson, G.C., 1986, Gold mineralization at the Homestake Gold Mine, Lead, South Dakota, in L.A. Clark, ed., *Gold in the Western Shield: Canadian Institute of Mining and Metallurgy Special Volume 38*, p. 347-358.
- Parslow, G.R., 1986, Kiseynew metallotect geochemical study, in R. Macdonald, T.I.I. Sibbald and D.F. Paterson, eds., *Summary of Investigations 1986, Saskatchewan Geological Survey: Saskatchewan Energy and Mines Miscellaneous Report 86-4*, p. 84-96.
- Parslow, G.R., and J.W. Gaskarth, 1985, Kiseynew metallotect geochemical study, in R. Macdonald, T.I.I. Sibbald and D.F. Paterson, eds., *Summary of Investigations 1985, Saskatchewan Geological Survey: Saskatchewan Energy and Mines Miscellaneous Report 85-4*, p. 50-58.
- Pearson, J.G., 1986, Kiseynew metallogeny: the geology of the Schotts Lake base metal deposit and Dolly gold occurrence, in R. Macdonald, T.I.I. Sibbald and D.F. Paterson, eds., *Summary of Investigations 1986, Saskatchewan Geological Survey: Saskatchewan Energy and Mines Miscellaneous Report 86-4*, p. 123-126.
- Pearson, J.G., F.H. McDougall, and A.G. Galley, 1986, Geology and evolution of gold occurrences in the Flin Flon - Amisk Lake area, Saskatchewan, in L.A. Clark, ed., *Gold in the Western Shield: Canadian Institute of Mining and Metallurgy Special Volume 38*, p. 399-411.
- Potter, D., 1980, Zinc-lead mineralization in the Wollaston Group stratigraphy, Siro-Fable Lakes area, Saskatchewan: unpublished M. Sc. thesis, University of Regina, Regina.
- Ramaekers, P., 1981, Hudsonian and Helikian basins of the Athabasca region, northern Saskatchewan, in R.H.A. Campbell, ed., *Proterozoic Basins of Canada: Geological Survey of Canada Paper 81-10*, p. 219-233.
- Rath, U., and R.D. Morton, 1969, Base metal occurrences in the Wollaston Lake belt of northern Saskatchewan: *Canadian Institute of Mining and Metallurgy Bulletin*, v. 62, no. 689, p. 961-966.
- Ray, G.E., and R.K. Wanless, 1980, The age and geological history of the Wollaston, Peter Lake and Rottenstone Domains in northern Saskatchewan: *Canadian Journal of Earth Sciences*, v. 17, p. 333-347.
- Richards, B.R., and B.G.W. Robinson, 1966, Mining and milling a small ore deposit — Rottenstone Mining Limited: *Canadian Mining and Metallurgical Bulletin*, v. 59, p. 1423-1428.
- Robertson, D.S., 1953, Batty Lake map-area, Manitoba: *Geological Survey of Canada Memoir 217*.
- Scott, B.P. 1973, The geology of the Pendleton Lake area (west half), Saskatchewan: Saskatchewan Department of Mineral Resources Report 154, 158 p.
- Sibbald, T.I.I., 1984, Gold metallogenic studies, Sulphide Lake area, in R. Macdonald and T.I.I. Sibbald, eds., *Summary of Investigations 1984, Saskatchewan Geological Survey: Saskatchewan Energy and Mines Miscellaneous Report 84-4*, p. 122.
- Sibbald, T.I.I., 1985, Geology and genesis of the Athabasca Basin uranium deposits, in R. Macdonald, T.I.I. Sibbald and D.F. Paterson, eds., *Summary of Investigations 1985, Saskatchewan Geological Survey: Saskatchewan Energy and Mines Miscellaneous Report 85-4*, p. 133-156.
- Sibbald, T.I.I., and D.E. Jiricka, 1986, Geology of gold deposits, Goldfields, Saskatchewan, in L.A. Clark, ed.,

- Gold in the Western Shield: Canadian Institute of Mining and Metallurgy Special Volume 38, p. 412-414.
- Stauffer, M.R., A.C. Mukherjee, and J. Koo, 1975, The Amisk Group: an Aphebian? island arc deposit: Canadian Journal of Earth Sciences, v. 12, p. 2021-2035.
- Tremblay, L.P., W.D. Loveridge, and R.W. Sullivan, 1981, U-Pb ages of zircons from the Foot Bay Gneiss and Donaldson Lake Gneiss, Beaverlodge area, northern Saskatchewan: Geological Survey of Canada Paper 81-1C, p. 123-126.
- Van Schmus, W.R., S.S. Persons, R. Macdonald, and T.I.I. Sibbald, 1986, Preliminary results from U-Pb zircon geochronology of the Uranium City region, in R. Macdonald, T.I.I. Sibbald and D.F. Paterson, eds., Summary of Investigations 1986, Saskatchewan Geological Survey: Saskatchewan Energy and Mines Miscellaneous Report 86-4, p. 108-111.
- Watters, B.R., 1986, Geochemistry and geochronology of metavolcanic and plutonic rocks in the Central Metavolcanic Belt, in R. Macdonald, T.I.I. Sibbald and D.F. Paterson, eds., Summary of Investigations 1986, Saskatchewan Geological Survey: Saskatchewan Energy and Mines Miscellaneous Report 86-4, p. 76-83.

PHANEROZOIC ROCKS IN SASKATCHEWAN — SOME REGIONAL AND GLOBAL TECTONIC IMPLICATIONS

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ABSTRACT

The wedge of Phanerozoic sedimentary rocks preserved within Saskatchewan forms the east-median segment of the Western Canadian Basin and the northwestern segment of the Williston Basin, and these two basins coincide more extensively within Saskatchewan than within any other province or state. The former basin is an interplate basin which developed at, and adjacent to, the ancient rifted margin of western North America. The basin's complex history may be resolved into a platform phase (Cambrian-Middle Jurassic) and a foreland-basin phase (Middle Jurassic-Paleocene), the difference between them well recorded in Saskatchewan rocks. The latter basin is an intraplate basin of problematic origin which developed on the continental crust of the North American Craton and lay on the eastern flank of the encompassing Western Canadian Basin.

Phanerozoic sedimentary rocks in Saskatchewan are readily divisible into the Sauk, Tippecanoe, Kaskaskia, Absaroka, Zuni, and Tejas unconformity-bound sequences. The stratigraphic spans of these agree so closely with positive fluctuations in the second-order cycles of global change in sea level that deposition of the sequences may be claimed to have been controlled eustatically. The sequences in Saskatchewan offer key evidence for reconstructing the history of the basins. The Sauk sequence preserves the distal edge of the earliest Phanerozoic transgressive-regressive cycle and predates the Williston Basin. The Tippecanoe sequence records marginal thinning and facies changes in the oldest rocks of that basin. Older Kaskaskia rocks carry the prime evidence of persistent evaporitic pans within the Williston Basin; younger Kaskaskia rocks of a second transgressive-regressive marine cycle show a prominent shoaling phase. Absaroka rocks, scarcely represented in Saskatchewan, betray restriction of the seas in the continental interior, the restriction to be correlated with unusually low stands of global sea level. The Zuni and Tejas sequences in Saskatchewan record expanding marine conditions, followed by the spread of continental conditions, which marked the evolution of the Western Canadian foreland basin in sectors well removed from the flanking orogen.

The new views of global and regional tectonics, and the broader based and more synthetic stratigraphic approaches they have spawned, are needed to explain further the Phanerozoic rock record in Saskatchewan and to contribute to understanding the genesis and emplacement of the economic natural resources that the rocks contain.

REGIONAL BASINS IN SASKATCHEWAN

LIMITS AND NAMES

Any review of Phanerozoic regional sedimentary basins based solely on the rocks of Saskatchewan must suffer from an unnatural limitation imposed by provincial boundaries. Geographically, these boundaries define an elongate trapezoid of the North American Craton, with Phanerozoic sedimentary rocks underlying the physiographic regions of the Central Lowlands and Great Plains in the southern two-thirds of the province. Stratigraphically, these boundaries limit the Phanerozoic sedimentary rocks to an uneven wedge, which tapers obliquely from southwest to northeast (Fig. 1) and is composed in its lower part dominantly of Paleozoic carbonate rocks and in its upper part dominantly of Mesozoic and Cenozoic terrigenous clastic rocks. Although the Saskatchewan wedge well illustrates the kinds of sediments that originally accumulated in the regional basins and the kinds of rocks and kinds of hydrocarbon and mineral concentrations that are preserved within them to this day, it

contributes little to defining the limits, and little more to understanding the origins and Phanerozoic history, of these basins. For an appreciation of such basic and broader issues, the Saskatchewan sedimentary wedge must be set in wider context, and such is the purpose of this paper.

Geologists may choose to view the wedge of Phanerozoic sedimentary rocks in Saskatchewan as the east-median segment of the Western Canadian Basin or as the northwestern segment of the Williston Basin — two basins, continental in their proportions, that coincide more extensively within Saskatchewan than within any other province or state. The Western Canadian Basin stretches from the edge of the Precambrian Shield in Manitoba and Saskatchewan to the Rocky Mountain Trench in British Columbia and from a little south of the northern boundary of the United States to a little north of the southern boundary of the District of Mackenzie and the Yukon Territory. Definition of the basin using geographical and geological criteria is somewhat artificial. Geologically, it embraces at least three distinct kinds of

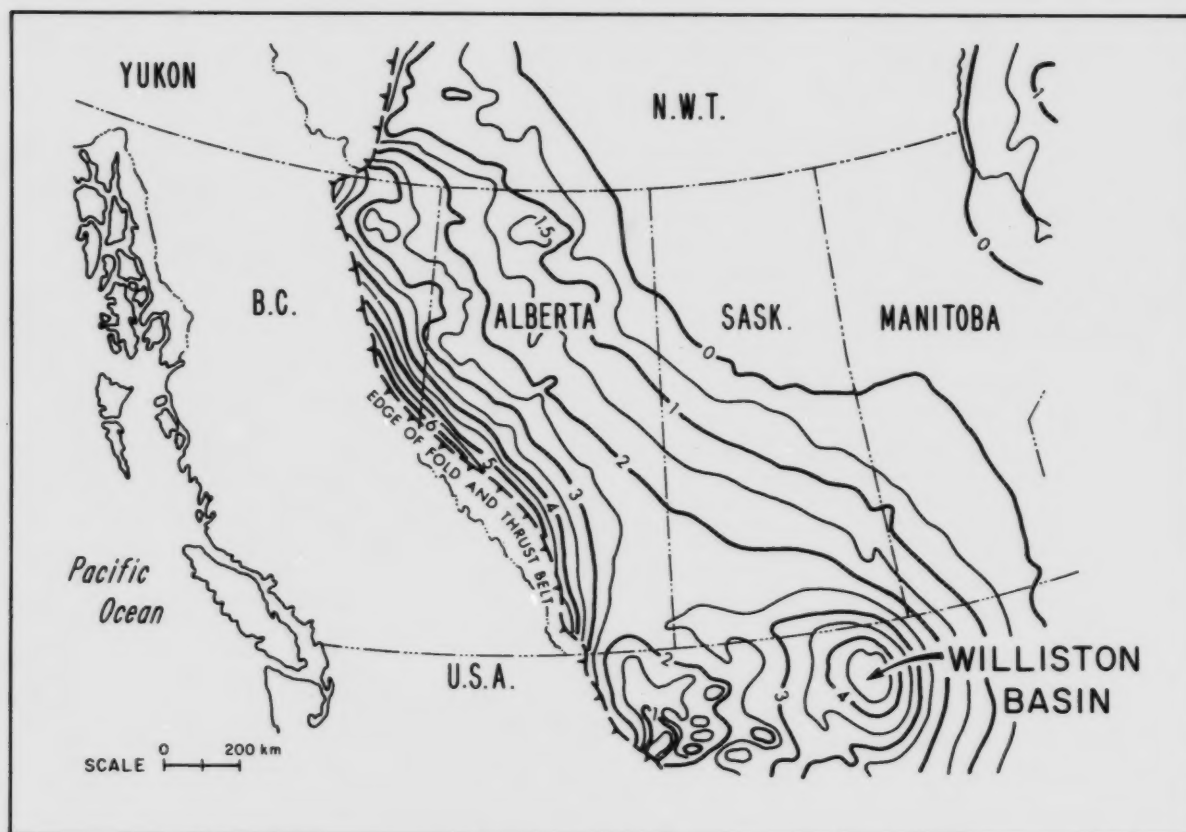


Figure 1. Total preserved thickness of Phanerozoic rocks in the Western Canadian Basin east of the fold and thrust belt of the Rocky Mountains and in the Williston Basin. Contours in kilometres. Modified after Porter et al (1982).

regional basins: for the first 420 Ma of the Phanerozoic Eon, it was a continental-margin basin of exceedingly complex history; for most of the remaining 150 Ma of the eon, a foreland basin of perhaps only slightly less complex history; and throughout the greater part of the eon, both continental-margin and superimposed foreland basins incorporated the intracratonic Williston Basin of seemingly simpler history. By contrast, the Williston Basin is much more naturally defined. Interpreted broadly but realistically to include what some would call its 'peripheral platform', the basin is bounded by a discontinuous ring of intracratonic arches which include the Severn, Wisconsin, Transcontinental, Sioux, Montana, and West Alberta (Porter et al, 1982). More obvious definition is provided, however, by circumscription of the entire basin by the erosional edge of its Ordovician rocks. These rocks crop out along the northeastern edge of the basin in eastern Saskatchewan and in Manitoba and along the southern edge in the mountain uplifts of southern Montana, northern Wyoming, and western South Dakota. Along the southwestern and northwestern edges of the basin in eastern Alberta and western Saskatchewan, the Ordovician rocks subcrop against overstepping younger rocks of Devonian and Cretaceous age. The annular outcrop pattern of many of the younger rocks, those of early Paleozoic age in particular, give added definition to both centre and periphery of the basin. Striking as that pattern may be, it has been shaped largely by pre-Middle Devonian erosion, and isopach maps, most notably of the Middle Ordovician sequence, reveal that the depositional basin was considerably larger and had quite a

different shape. Throughout Phanerozoic time, the Williston Basin behaved as a gently subsiding trough, subcircular in outline and saucer-like to shallow cone-like in three-dimensional form, although in its later history, the epeirogenic movements of the bounding arches and of the basin itself were influenced by orogenic movements on the western flank of the Western Canadian foreland basin.

The degree of arbitrariness that convenience has insinuated into definition of both the Western Canadian and Williston Basins is exposed by the sedimentary pattern that prevailed at certain times during the Phanerozoic Eon. Thus, for example, in the Late Cretaceous Epoch, the main facies belts transgressed the boundaries of both basins with seeming indifference because the regions underlain by these basins were then unexceptional tracts of the much larger Western Interior Basin of North America (Caldwell, 1982).

ORIGINS

Despite the relationship implied by their overlap, the Western Canadian and Williston Basins have quite different origins and developed differently through the greater part of Phanerozoic time. The evolution of the Western Canadian Basin is inextricably linked to that of the adjoining Cordillera. Through Paleozoic and early Mesozoic times, the basin was characterized by a gently (if unevenly) subsiding cratonic platform. Initially, subsidence of the western margin of the platform may have resulted from cooling, subsequent to

stretching and rifting, of the North American Precambrian lithospheric plate and from isostatic adjustment to "the weight of sediments that had accumulated at the margin in...[an] oceanward prograding continental terrace wedge" (Porter et al, 1982). Subsidence then may have been sustained by further deposition of sediment during prolonged and repeated inundations of all, or vast tracts, of the platform by epeiric seas transgressive from the west, but it was also profoundly influenced by the development of cratonic basins, such as the Williston, bounded by arches, with more continuous and heavier sedimentation taking place in the basins. In later Mesozoic and early Cenozoic times, the Western Canadian Basin was transformed into an exogeosyncline (Kay, 1951) or a foreland basin (Price, 1973; Beaumont, 1981; Beaumont et al, 1982) initially by accretion, following collision, of two of the exotic terranes of the Cordillera to the western margin of the continent and eastward displacement of later Proterozoic and Phanerozoic rocks onto the Craton. Progressive eastward encroachment and stacking of these supracrustal rocks in a series of thrustbound slices led to the incorporation into the fold-thrust belt of some successive deposits of the basin itself, as the basin was displaced eastwards in advance of the orogenic front (the 'migrating foredeep' of Bally et al, 1966). Continued subsidence then became a response to loading and viscoelastic warping of the lithospheric plate, with the load emplaced by both tectonic and non-tectonic processes. Within the orogen, the magnitude of the tectonic load, which can be measured by the degree of crustal shortening, exceeded the rate of mass wasting, and strongest subsidence took place in the west (the foredeep of the basin), adjoining the mountain front. Within the basin, synorogenic sediments were spread as a huge wedge, thickest in the west, which enhanced differential loading and, in consequence, differential subsidence across the trough. The asymmetrical form of the basin thus was determined by overall magnitude and position of load and by the properties of the cool, thick, old lithospheric foundation which caused that foundation to behave with considerable flexural rigidity. Consonant with this interpretation, uplift and denudation of the basin may be correlated with deep and widespread erosion of the fold-thrust belt wherein the maximum load was concentrated.

The Western Canadian Basin then accords with Reading's (1982) thesis that most regional sedimentary basins may be explained by global tectonic processes. It is to be categorized as an interplate basin which developed along a continental margin which was, at different times, active and passive. Although the complete tectonic history of the western margin of the North American lithospheric plate in what is now western Canada is far from fully understood, the complexity of that history, involving episodes of crustal extension, rifting, collision, obduction, and subduction, is evident from a growing weight of circumstantial and direct evidence.

In Reading's terminology, the Williston Basin is, in contrast, an intraplate basin developed on continental crust. More specifically, it is one of the largest intracratonic basins in North America, and the origin and enduring growth of intracratonic basins remains perhaps the most fundamental unresolved problem of cratonic geology. The problem is multifaceted. How did the basins originate? Why did they develop when and where they did? How were their epeirogenic movements controlled? Is their relative subsidence as much a function of uplift on their bounding arches as of subsidence of the basins themselves?

Much less agreement exists about the origin of the Williston Basin than about that of the Western Canadian Basin. The simplistic view that subsidence is a response to loading of the crust with an incremental pile of sediments, the increments to be correlated with the higher stands of a fluctuating global sea level, is unacceptable because such loading is inadequate to account for the amplitude of the subsidence (Sleep et al, 1980; Watts and Steckler, 1981). Applying some of the numerical calculations of Sleep et al (1980) to the Williston Basin, Nisbet and Fowler (1984) determined that the total thickness of sediment that could accumulate subaqueously is measured by the depth of the basin multiplied by a density factor of about 3.25. Given that the basin contains about 4.7 km of lithified sediments, they calculated that the basin was a crustal depression of about 1.5 km, the subsidence of which was augmented by such sedimentary fill as accumulated with basin growth. Although heating and subsequent depression may adequately explain the subsidence of basins at rifted continental margins, when thermal models are applied to intracratonic basins (Haxby et al, 1976) they cannot be reconciled with the character and rate of subsidence that distinguish such basins as the Williston (Sloss, 1982; Nisbet and Fowler, 1984; Fowler and Nisbet, 1985). As Sloss (1982) explained, Falvey (1974) invoked thermally related phase changes in the crust to create subsidence and Middleton (1980) applied Falvey's postulates to intracratonic basins, but the evidence for localized heating events and their consequences in these cratonic basins is lacking.

In considering the origin of the Williston Basin, certain key pieces of evidence must be accommodated to any explanatory theory:

- 1) Seismic refraction experiments have shown that the basin is underlain by a thick crust of 50 to 55 km and that thickness increases toward the basin centre (Warren and Healy, 1973; Hajnal and Fowler, 1982; Hajnal et al, 1984). Hence models of basin formation that invoke attenuation of the crust can be discounted.
- 2) Analysis of subsidence within the basin strongly suggests that the subsidence is not exponential, that is, it does not slow down with time, which supports the seismological evidence against any form of lithospheric extension (Fowler and Nisbet, 1985).
- 3) Although the basin must have resulted from loading and crustal flexure, the load was not a superimposed one, emplaced by overthrusting. Throughout most of its history, the Williston Basin was not a foreland basin; only in the Cretaceous Period did the basin come under the influence of the distal sedimentary load shed into the Western Canadian Basin during its foreland-basin phase. The non-exponential pre-Cretaceous subsidence rate accords with this view.
- 4) The sedimentary record of the basin's Phanerozoic history is notably incomplete, with more of Phanerozoic time represented by unconformities than by rock. Such rocks as remain within the basin accord closely with the unconformity-bound sequences of Sloss (1963) and correlate with the episodes of second-order high stand in the graph (Vail et al, 1977; Vail and Mitchum, 1979) of fluctuating global sea level and coastal onlap..

eastern flank of an embracing interplate basin, the complex Phanerozoic history of which may be resolved into an early platform phase and a later foreland-basin phase.

STRATIGRAPHIC SEQUENCES

PERSPECTIVES OLD AND NEW

The stratigraphy of the rocks that fill the Williston Basin has been well described in a literature that spans more than three decades. Some excellent syntheses have been prepared of certain of the more important unconformity-bound stratigraphic sequences in large segments, or in all, of the basin, and these sequences have been related to coeval sequences in other parts of the continent (see, for example, the lower Paleozoic sequences — Porter and Fuller, 1959; Fuller, 1961; Patterson, 1961; Fuller and Porter, 1962). Regional distribution of all of the sequences is described in two atlases: the 'Geological History of Western Canada' (McCrossan and Glaister, 1964) and the 'Geologic Atlas of the Rocky Mountain Region' (Mallory, 1972), and a plethora of more detailed studies are contained in the proceedings of four international symposia on the Williston Basin, published by the Billings, North Dakota, and Saskatchewan Geological Societies between 1956 and 1982, and in a wide variety of other publications. Modern reviews of the evolution of the basin, with respective emphasis on energy resources and regional tectonic setting, have been prepared by Gerhard (1982) and by Porter et al (1982). Clearly, any kind of regional synthesis based on detailed examination of the stratigraphic record would be largely redundant. What is entirely pertinent to this review, however, is a highlighting of those aspects of the major stratigraphic sequences within Saskatchewan which have had a central place in reaching present understanding of the evolution of the Williston Basin and the Western Canadian Basin. To set the stratigraphic record within Saskatchewan in an even wider context, the main depositional episodes, as expressed mainly by Sloss's (1963) unconformity-bound sequences, are compared to the cycles of global change in sea level and coastal onlap proposed by Vail et al (1977) and Vail and Mitchum (1979). The comparison is given added point by the omission of the stratigraphic record in the Williston Basin and other North American intracratonic basins from the compilations of world-wide data made by these authors.

Vail et al (1977) recognized three major orders of cycles of relative change in global sea level in their curve for Phanerozoic time. Cycles of the first order (two recognized) have durations of 200 to 300 Ma; those of the second order (over 14 recognized) have durations of 10 to 80 Ma; and those of the third order (about 80 recognized) have durations of 1 to 10 Ma. Because sea-level changes from Cambrian through Early Triassic times are not as well described globally as those from Late Triassic through Holocene time, third-order cycles were not identified in the lower part of the Phanerozoic column. Geotectonic and glacial phenomena are held to be the most likely causes of the eustatic cycles. The 'Vail curve' (Fig. 2) depicts relative changes in sea level on a global scale and, although they are possibly strongly related, these changes are not to be confused with transgressions and regressions of shorelines on a global scale. Modifications have to be made in the 'Vail curve' to give approximations of the times of

transgressive peaks and regressive troughs, a procedure which raises some difficulty in testing the eustatic hypothesis by conventional biostratigraphic methods. This has been discussed by Caldwell (1984). The pre-Cretaceous Williston Basin should make an ideal testing-ground for assessing the validity of the 'Vail curve'. Being an intracratonic basin, well removed from any orogen and thus negligibly deformed by tectonic processes, its history of deposition should not have been affected significantly by fluctuations in sea level instigated by regional tectonics and it should be expected to bear a reasonably faithful signature of eustatic fluctuations. Within the Williston Basin, generalized application of the 'Vail curve' has been made to the pre-Cretaceous succession by Fowler and Nisbet (1985). Prior to that, five major marine cycles of transgression and regression recognizable in the Cretaceous System had been compared to a series of global transgressions and regressions and these, in turn, related to third-order fluctuations in the 'Vail curve' by Caldwell (1982, 1984).

The sequences preserved within various sectors of Saskatchewan and adjoining regions are summarized in Table 1.

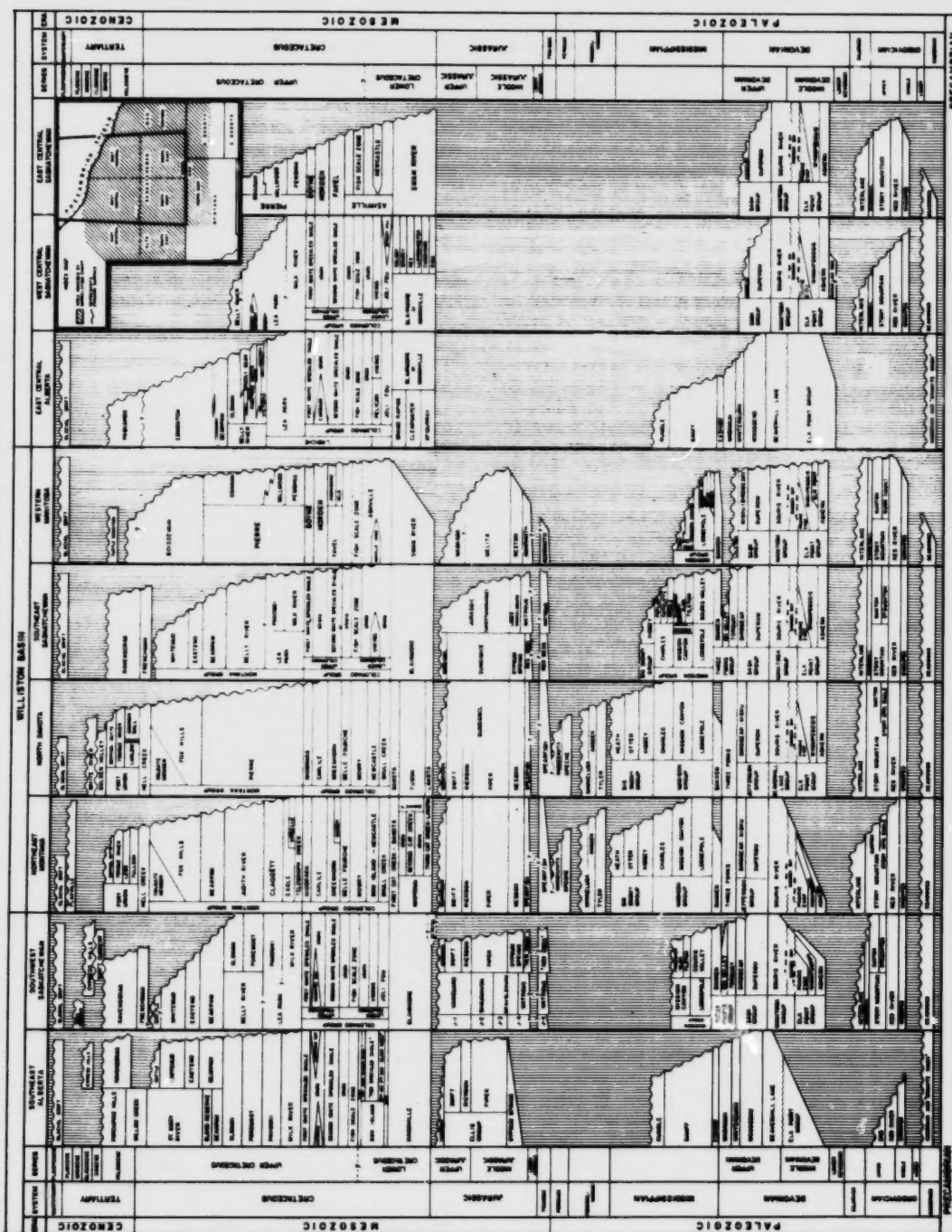
THE MIDDLE CAMBRIAN-LOWER ORDOVICIAN SAUK SEQUENCE*

The Sauk sequence records the earliest marine inundation of the Precambrian Craton in Phanerozoic time. In extending farther onto the continental platform with time, the Cambrian seas underwent pulsed transgression: Lower Cambrian rocks are overlapped by Middle Cambrian rocks and Middle Cambrian rocks by Upper Cambrian and Lower Ordovician rocks. The base of the Sauk sequence is marked by a veneer of fairly clean quartz sandstone deposited as a diachronous sheet which becomes progressively younger as it is traced towards the continental interior. The top of the sequence is bevelled by regional unconformities. Middle and Upper Cambrian and Lower Ordovician rocks across the Western Canadian Basin form a composite northeast-tapering wedge, the original sediments having been deposited in shallow epicratonic seas which reached inland north of the old domal massif of 'Montania'. These rocks contain the deposits of several marine cycles distinguished by lateral shift in three main lithofacies: a lower terrigenous clastic facies characterized by sandstones, siltstones, and shales; a middle carbonate facies identified by bank and sheet limestones; and an upper terrigenous clastic facies marked by calcareous shales (Porter et al, 1982).

Given that general understanding of the Sauk sequence, the contribution of the rocks preserved in Saskatchewan has been to provide critical information about the depositional limits of the transgressive Cambrian seas, the facies characteristic of distal deposits in the transgressive-regressive sedimentary wedge, and the rapid Early Ordovician regression of the sea and subsequent erosion of the Sauk deposits. Middle and Upper Cambrian and some Lower Ordovician rocks occur in Saskatchewan in successively onlapping wedges which thin mostly by attenuation (Fuller and Porter, 1962). From the variations in thickness and the positions of the present erosional edges, the strandline position of the Middle Cambrian sea has been reconstructed well within southwestern Saskatchewan and that of the Late Cambrian sea well beyond

* Modification of the Sauk and subsequent sequences by adding their stratigraphic spans within the Williston Basin and, generally, within Saskatchewan is done solely for convenience. Disagreement with Sloss's (1963) remarks on his sequence terminology is not implied.

Table 1. Stratigraphic correlation chart for Saskatchewan and adjoining areas, modified from the chart published by the Saskatchewan Department of Mineral Resources, Petroleum and Natural Gas Branch, in 1963.



the border with Manitoba (Porter et al, 1982). The entire Sauk sequence in Saskatchewan is composed of an assemblage of heterogeneous terrigenous clastic rocks which resemble those of the Emerson Formation in the Little Rocky Mountains of Montana or the Deadwood Formation of the Black Hills of South Dakota, the latter formational name commonly being applied to the Saskatchewan rocks (Table 1). The internal cyclicity of the Sauk sequence, so distinctive in the limestone-bearing successions farther west, is essentially lost in the near-shore deposits of Saskatchewan. The remains of Sauk trilobites permit a crude biostratigraphy to be superimposed on the uniform lithostratigraphy of the Saskatchewan sequence. Sufficient to establish the relative ages of the rocks, the trilobites have been used to expose facies equivalency to the thicker and better differentiated lithostratigraphic successions farther west in Alberta and to reveal that the unconformity truncating the Sauk sequence all across Saskatchewan is sculptured in Early Ordovician (Tremadocian) rocks. That unconformity resulted solely from pre-Middle Ordovician erosion. Beyond Saskatchewan, where the protective cover of Middle Ordovician carbonate rocks was removed, the Sauk sequence was much more deeply stripped by the combined forces of pre-Middle Ordovician and pre-Middle Devonian erosion.

The Sauk sequence in Saskatchewan is critically important in constraining the time of formation of the Williston Basin. Both in its preservation as a simple northeasterly and uniformly tapering wedge and in the approximate parallelism of its isopachs and the depositional strike, the Sauk sequence betrays that no basin existed when the sediments were deposited. The Williston Basin did not form until after earliest Ordovician time.

Progressive inundation of the cratonic platform in Cambrian and Early Ordovician time is fully in agreement with the gradual rise in global sea level reconstructed by Vail et al (1977). These authors show maximum coastal aggradation associated with rising sea level and coastal onlap for both the Paleozoic first-order cycle and the earliest Phanerozoic second-order cycle as being attained in the Early Ordovician Epoch. The transgressive peak, therefore, may have been attained a little earlier, which would accord with the rapid regression, culminating in the pre-Middle Ordovician unconformity, being recorded in the earliest Ordovician (Tremadocian) rocks of the Williston Basin in Saskatchewan.

THE MIDDLE ORDOVICIAN-UPPER SILURIAN TIPPECANOE SEQUENCE

The Williston Basin came into being about the end of the Early Ordovician Epoch, just when the Tippecanoe sequence began to be deposited. That sequence is dominated by shallow-water shelf carbonates, now preserved as the dolomites and selectively dolomitized limestones of the Bighorn and Interlake Groups, but it does contain other rocks that, although volumetrically insignificant, warrant special attention if only because they are different. Most notable among these are the quartz sandstones and overlying shales of the Winnipeg Group, which floor most of the central Williston Basin and thin to disappear peripherally where they are overlapped by the lowest carbonate formation of the Bighorn Group, the Red River (Table 1). Much of the sand and other terrigenous sediment was derived by reworking of the Upper Cambrian deposits over the bounding arches and farther afield. Notable too are six thin but persistent evaporite deposits, three in the

upper Red River Formation, one in the upper Stony Mountain Formation, and two in the Stonewall Formation (Fuller and Porter, 1962), restricted to the central part of the basin. Each of these anhydrite deposits terminates a distinct sedimentary rhythm grading from organic-fragmental limestone, through increasingly precipitated forms of limestone, to anhydrite. Such rhythms point to periodic shallowing, with restricted circulation and concentration of the brines, brought about by emergence of the arches bounding the basin (Porter et al, 1982). By plotting the locus of maximum deposition of the various components of the Tippecanoe sequence, migration of the Williston Basin's depocentre over distances well in excess of 100 km during Middle Ordovician to Late Silurian time can be demonstrated.

Extending in places to the edge of the Precambrian Shield, the Tippecanoe rocks in Saskatchewan offer the longest radial section through the preserved Middle Ordovician to Middle Silurian rocks of the Williston Basin (Fig. 3) and thus reveal to the greatest extent the kinds of changes that these rocks undergo between basin centre and perimeter. Traced northward from the centre, around Williston, the various components of the Ordovician succession gradually lose their identity (Patterson, 1961). The Winnipeg Group (Paterson, 1971) is eliminated by overlap in western Saskatchewan, and the rhythmic deposits with their evaporite markers (Kent, 1960), like the associated limestones and dolomitized limestones, pass by facies change into dense, fine-grained dolomites which give way in upward sequence to the pale-coloured, fine-grained dolomites of the Silurian Interlake Group (Jamieson, 1979). The entire Tippecanoe sequence thins northwards towards the periphery of the basin, as it does too in other radial directions, and as Porter et al (1982) have pointed out this is a combined consequence of attenuation and condensation of the sequence as the surrounding arches are approached and of pre-Middle Devonian uplift and truncation.

The Tippecanoe rocks in Saskatchewan and elsewhere in the Williston Basin contain fossil assemblages dominated by algae, solitary rugose and tabulate corals, stromatoporoids, and nautiloid and gastropod molluscs (Brindle, 1960). The most distinctive fauna is that of the Red River Formation, which has been traced in extensive remnants of lithologically similar, coeval beds from Greenland, through the western interior of North America, to New Mexico. From the character and distribution of the fauna, Nelson (1959a, b) suggested that it was a shallow, warm-water equatorial assemblage, an interpretation subsequently confirmed by paleomagnetic studies between northwestern Greenland and the Gulf of California.

Major falls in global sea level are predicted by Vail et al (1977) to have occurred near the end of the Early Ordovician and the beginning of the Early Devonian Epochs, with a weakly fluctuating, but prolonged and significant, high stand between them. This accords well with the record of Tippecanoe sedimentation, which spanned Middle Ordovician to Late Silurian times and which was preceded and succeeded by intervals of widespread subaerial erosion. The Vail curve is apparently at variance with the sedimentary record in the Williston Basin on only two points. The Middle to Late Ordovician carbonates of the Bighorn Group and its equivalents seem to have been the most widespread of the Tippecanoe sequence in the basin and throughout other parts of western North America and could have been expected to

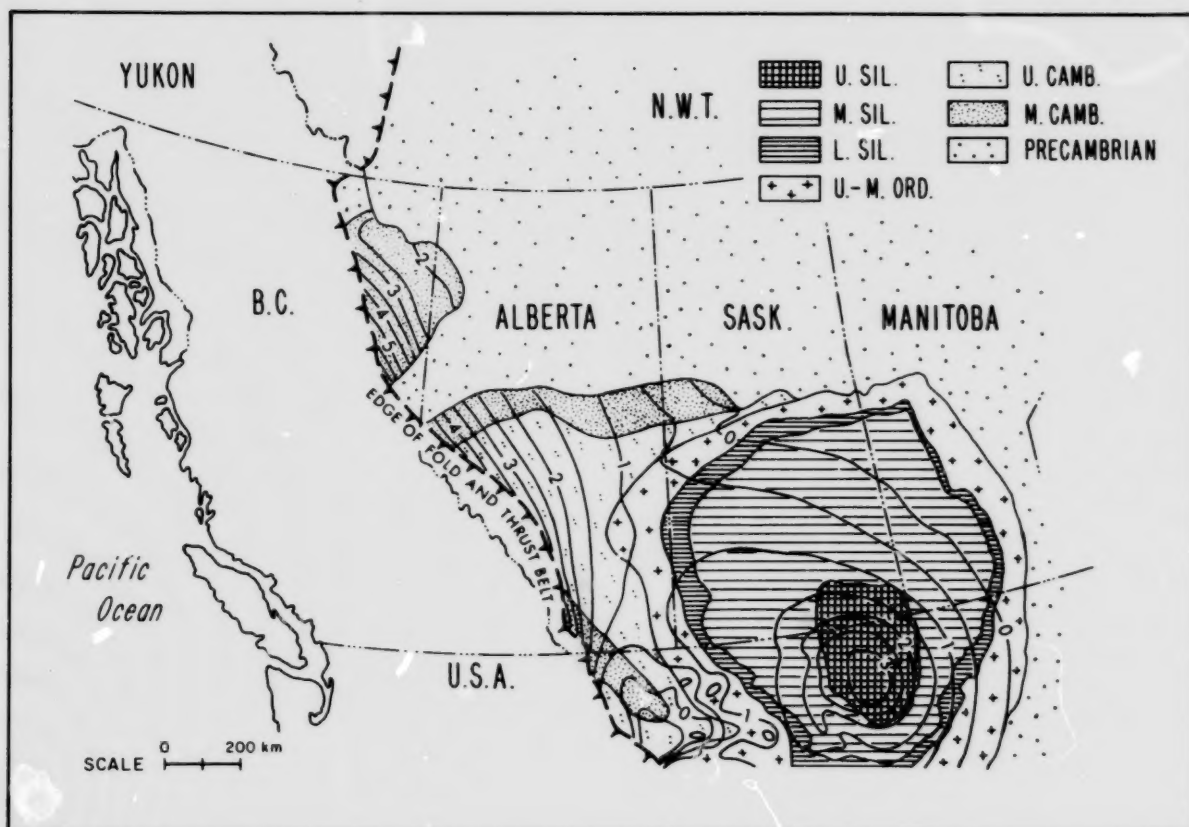


Figure 3. Geology and structure of the pre-Devonian (Post-Tippecanoe — pre-Kaskaskia) erosional surface. Note the annular outcrop pattern in the Tippecanoe sequence, but not in the Sauk sequence, of the Williston Basin. Contours in kilometres. Modified after Porter et al (1982).

correspond to the highest stand of the seas during the Ordovician and Silurian Periods. Yet the Vail curve shows the highest stand to have been attained in the Middle Silurian Epoch. Even more anomalous is the indication that the dramatic rise in global sea level in the Late Cambrian and Early Ordovician Epochs exceeded that attained subsequently in the Ordovician and in the Silurian Periods. These seeming discrepancies may be of no great significance; the magnitude of a rise in global sea level need not necessarily correlate precisely with the magnitude of a marine transgression in part of a continent.

THE MIDDLE DEVONIAN-UPPER MISSISSIPPIAN KASKASKIA SEQUENCE

Although the Tippecanoe sequence becomes notably condensed between the core and periphery of the Williston Basin, each major component of the sequence, from the Winnipeg Group at the base to the Interlake Group at the top, has some representation in all northern sectors of the basin. This stands in contrast to the succeeding Kaskaskia sequence, in which both the thickness and the number of component elements become progressively reduced from the basin's centre to its margins (Table 1). Such reduction should not be taken to imply that erosional stripping of the Tippecanoe sequence, prior to deposition of the Kaskaskia sequence, was even and negligible. On the contrary, as Porter et al (1982) have stressed, the onset of Kaskaskia sedimentation was preceded by profound epeirogenic deformation in Early Devonian time,

and the distribution, kind, and thickness of the initial Kaskaskia deposits were controlled by relief on the eroded surface. Effects were most strongly registered on the arches beyond the Williston Basin, but erosion conferred on the basin the asymmetric subcircular outline so well defined by the annular outcrops and subcrops of successive Tippecanoe components (Fig. 3), only weakly related though that outline may be to that of the Ordovician depositional basin. Breaching of the Tippecanoe carbonate cover and subsequent erosion of less-resistant terrigenous clastic rocks of the Sauk sequence resulted in the Meadow Lake Escarpment of west-central Saskatchewan, which bounded the northwestern flank of the basin, and deeper erosion of parts of the Severn and Transcontinental Arches and of the Sioux Arch was particularly important in determining the configuration of the northeastern and southeastern flanks of the pre-Kaskaskia basin. Relief of the pre-Kaskaskia surface required the new transgressive sea of Middle Devonian time to invade the Williston Basin from northwest to southeast, rather than from the west as preceding seas had done (Porter et al, 1982).

Within the Saskatchewan portion of the Williston Basin, the Middle Devonian Elk Point Group records the initial marine inundation that began late Paleozoic or Kaskaskia deposition; it is recorded in the dolomites, limestones, and carbonate-bank deposits of the Winnipegosis Formation (Jones, 1965), which succeed the thin, red and grey dolomites and shales of the Ashern Formation and are succeeded by the thick salt deposits

of the Prairie Evaporite Formation (Holter, 1969; Meijer Drees, 1986). The migration of salt-pan conditions, which had become established north of the Meadow Lake Escarpment in early Middle Devonian time, into the Williston Basin in late Middle Devonian time, and the persistence of these conditions within the basin into Late Devonian time (Porter et al, 1982), may have stemmed from progressive southward shift of a series of barrier reefs. These reefs restricted open-marine conditions to the northwest and permitted precipitation of the economically important potash-bearing evaporites throughout a broad belt of Saskatchewan only. Fairly even deposition of the restricted-marine sediments that produced the carbonate-dominated formations of the Manitoba, Saskatchewan, and Three Forks Groups and their equivalents within, and beyond, the province (Kents, 1959; Christopher, 1961; Kent, 1963, 1968; Lane, 1964; Nichols, 1970; Dunn, 1975, 1982) essentially eliminated differentiation of the basin from its flanking shelves during most of the late Middle and Late Devonian Epochs and heralded the brief episode of widespread tectonic stability marked by the dark shales of the Bakken and equivalent formations at the base of the Mississippian succession. Beyond the southern boundary of Saskatchewan, however, the Upper Devonian formations overlap the Middle Devonian formations to become banked against the Transcontinental and Sioux arches.

Pre-Absaroka (earliest Pennsylvanian) and intra-Absaroka (Pennsylvanian-Permian) erosion bevelled the upper part of the Kaskaskia sequence within Saskatchewan to a degree that a reasonably complete Mississippian succession is present only in the southeastern part of the province. That succession begins with the thin organic-rich shales of the Bakken Formation, ranges through the thin-bedded limestones and calcareous shales of the Lodgepole or Souris Valley Formation, the thick-bedded biofragmental and oolitic limestones of the Mission Canyon Formation, and the carbonate-evaporite rhythms of the Charles Formation, all three composing the Madison Group, into the sandstones and shales of the Kibbey Formation at the base of the overlying Big Snowy Group (Fuller, 1956; Edie, 1958; Porter, 1958; Fuzesy, 1960, 1966, 1973; Kent, 1974). The various Madison lithotypes rise diachronously southwestwards and may be interpreted in terms of the 'upward-shoaling' model of Wilson (1975) or the 'progradational' model of Macqueen and Bamber (1968). What the Mississippian rocks of southeastern Saskatchewan reveal more clearly than elsewhere in the Williston Basin is that most of the deposition took place with slow marine regression subsequent to much more rapid transgression early in Mississippian time. In southwestern Saskatchewan, the Mississippian succession was truncated to the level of the Mission Canyon Formation and, influenced also by pre-Cretaceous erosion, in east- and west-central Saskatchewan it was removed completely (Table 1).

Vail et al (1977) have inferred a low stand of global sea level in earliest Devonian time, an even lower stand in earliest Pennsylvanian time, and between them, a eustatic rise with its acme at the end of Early Mississippian time. The record of marine deposition in the Kaskaskia sequence of the Williston Basin conforms well to this clearly defined second-order cycle. Within Saskatchewan, the evaporite-pan conditions of the Middle Devonian Epoch and the less than completely open-marine conditions of the Late Devonian Epoch stemmed from the location of barrier reefs beyond the basin and the extent of the weakly inundated marine platform across the basin. The more open-marine conditions of the northwest gradually

migrated southeastwards during these epochs. Although the sedimentary record within the North American Craton as a whole would deny it (Sloss, 1963), the record in the core of the Williston Basin might be read as suggesting a minor sea-level fluctuation between the Devonian and Mississippian Periods. A discrete marine cycle is recorded in the Mississippian rocks: the transgressive phase, beginning above a localized sub-Bakken disconformity, spans most of Early Mississippian time, and the regressive phase spans the remainder of Mississippian time. Late Devonian regression and Early Mississippian transgression within the core of the basin more probably resulted, however, from reactivation of the arches to the east and south or from emergence of the Central Montana Uplift. Porter et al (1982) suggested that emergence of that uplift created the barrier behind which the Upper Mississippian evaporites were precipitated and that rejuvenation of the arches brought about deposition of the uppermost Mississippian sands and silts (formations of the Big Snowy Group preserved only around Williston in North Dakota). Be that as it may, the two-phase drop in global sea level (first at the end of Early, second at the end of Late Mississippian time), inferred by Vail et al (1977), could have been as important as local epeirogenic events in creating the environments in which these Upper Mississippian sediments were deposited.

THE LOWER PENNSYLVANIAN-LOWER JURASSIC ABSAROKA SEQUENCE

The Absaroka sequence in the Williston Basin is bounded by inter-regional unconformities which record erosion in earliest Pennsylvanian and Early Jurassic times and is disrupted by regional unconformities which mark erosion in latest Pennsylvanian and latest Permian-earliest Triassic times. Deposits are thin, and most of them are restricted to the core of the Williston Basin in northwestern North Dakota and northeastern Montana (Fig. 4 and Table 1). Although the depositional edge of both the Pennsylvanian and Permian basins may have extended as far north as the southernmost strip of present-day Saskatchewan, rocks of these ages were removed during the episodes of infra-Absaroka erosion, and all that remains of the Absaroka sequence within Saskatchewan today are thin red beds and associated evaporites, commonly grouped as the Triassic (Lower) Watrous Formation, in the southeastern and southwestern segments of the province (Table 1).

The Absaroka record is a product of two regional structural events which have been outlined by Porter et al (1982): emergence and westward tilt of the entire cratonic platform leading to eastward attenuation and intermittent erosional beveling of the sequence, and emergence of the northeast-trending Sweetgrass Arch in Early Pennsylvanian time to persist as a facies-separating barrier until Middle Jurassic time. Whereas marine deposition occurred northwest of the arch, predominantly non-marine deposition prevailed southeast of the arch, in the Williston Basin, where some sands and silts were derived by long-range dispersal from the ancestral Rocky Mountains in the United States during the waning phases of Paleozoic time and evaporites (halite) and red beds accumulated mainly during the initial phases of Mesozoic time.

The two regional events, however, acted in concert with global events. Late in the Early Permian Epoch and again in the Early Jurassic Epoch, global sea level fell below even the unusually low level of the present day; indeed from earliest Pennsylvanian through Early Jurassic time, global sea levels

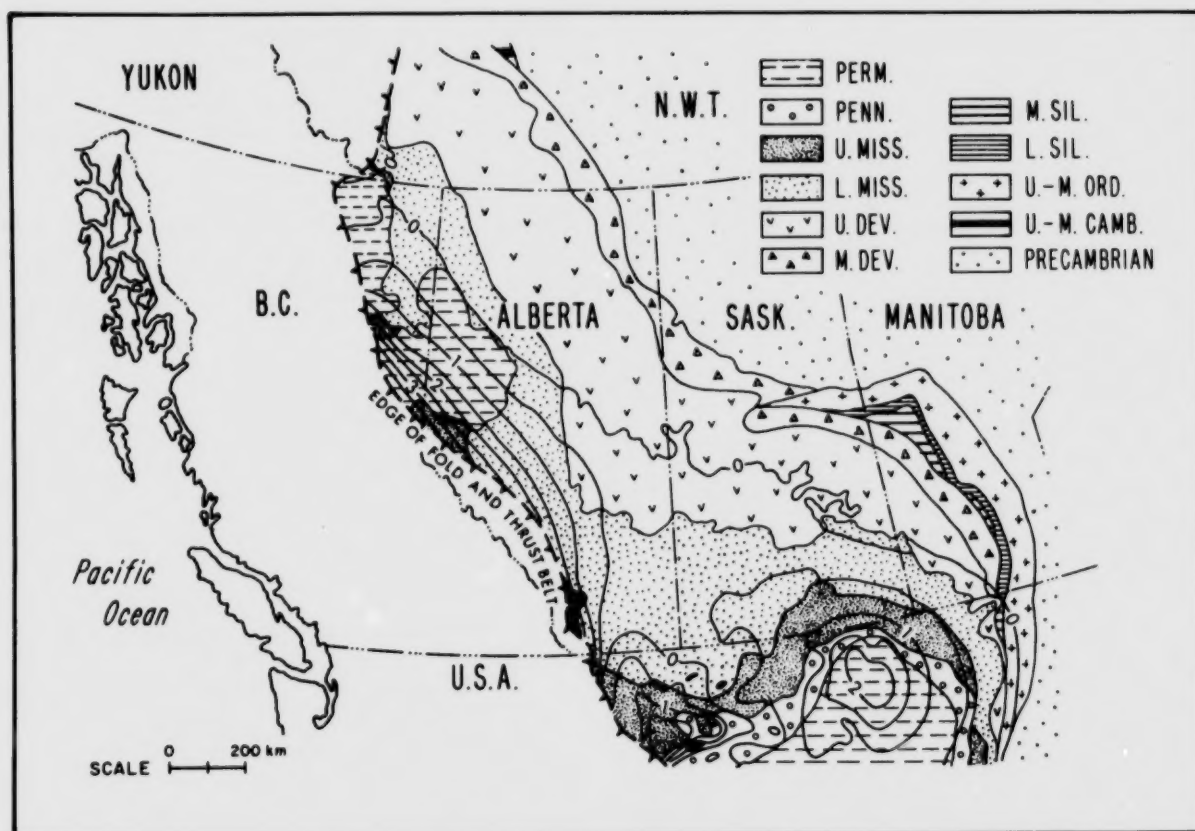


Figure 4. Geology and structure of the pre-Mesozoic erosional surface. As the Absaroka sequence is only locally and thinly preserved in Saskatchewan, the map of the province is essentially one of the post-Kaskaskia — pre-Zuni surface. Contours in kilometres. Modified after Porter et al (1982).

stood at their lowest of the entire Phanerozoic Eon, and the low stand of Early to Middle Triassic time marks the boundary between the two Phanerozoic first-order cycles of Vail et al (1977). Although the succession of latest Paleozoic-earliest Mesozoic fluctuating low stands doubtless is rooted in contemporary global tectonic events, a major contributing factor must have been the late Paleozoic glaciation of the southern hemisphere (Gondwanaland). Given contemporary global and regional events derived from beyond the Williston Basin, the character of the Absaroka sequence within the basin is entirely to be expected. The thin evaporites and red beds in the southern sectors of Saskatchewan — sole remnants of an Absaroka sequence that never was widely spread — are perhaps principally related to one of the most positive fluctuations of global sea level during the prolonged period when the world's seas stood unusually low. During the Triassic Period, marine waters, transgressing northeastwards across a shallow shelf through Wyoming, eastern Montana, and western North Dakota, seem to have expanded weakly into southern Saskatchewan, east of the Sweetgrass Arch. In general, however, Saskatchewan says more about the global and regional events of Early Pennsylvanian to Early Jurassic time by the absence of Absaroka rocks (Fig. 4) than by the presence of the one thin sequential representative.

THE MIDDLE JURASSIC-PALEOCENE ZUNI SEQUENCE AND THE POST-PALEOCENE TEJAS SEQUENCE

With deposition of the Zuni sequence, an entirely different sedimentary regime was introduced to the Williston Basin. Whereas in the earlier sequences carbonates and evaporites had been dominant, in the Zuni and Tejas sequences terrigenous clastic sediments were overwhelmingly preponderant. Moreover, whereas the earlier terrigenous clastic sediments interspersed with the carbonates and evaporites substantially were derived by erosion of the arches and platform surrounding the basin (even though some were introduced by seas transgressive from the northwest, west, and southwest), the terrigenous clastic sediments of the Zuni and Tejas sequences were derived from the Cordillera and spread eastwards across the basin in a gradually thinning blanket (Fig. 5).

As Porter et al (1982) pointed out, the controls on erosion and sedimentation during the Middle Jurassic initiation of the Zuni sequence basically were those that had prevailed during deposition of the prior Absaroka sequence. Persistence of the Belt Island-Sweetgrass Arch led to the deposition of sediments

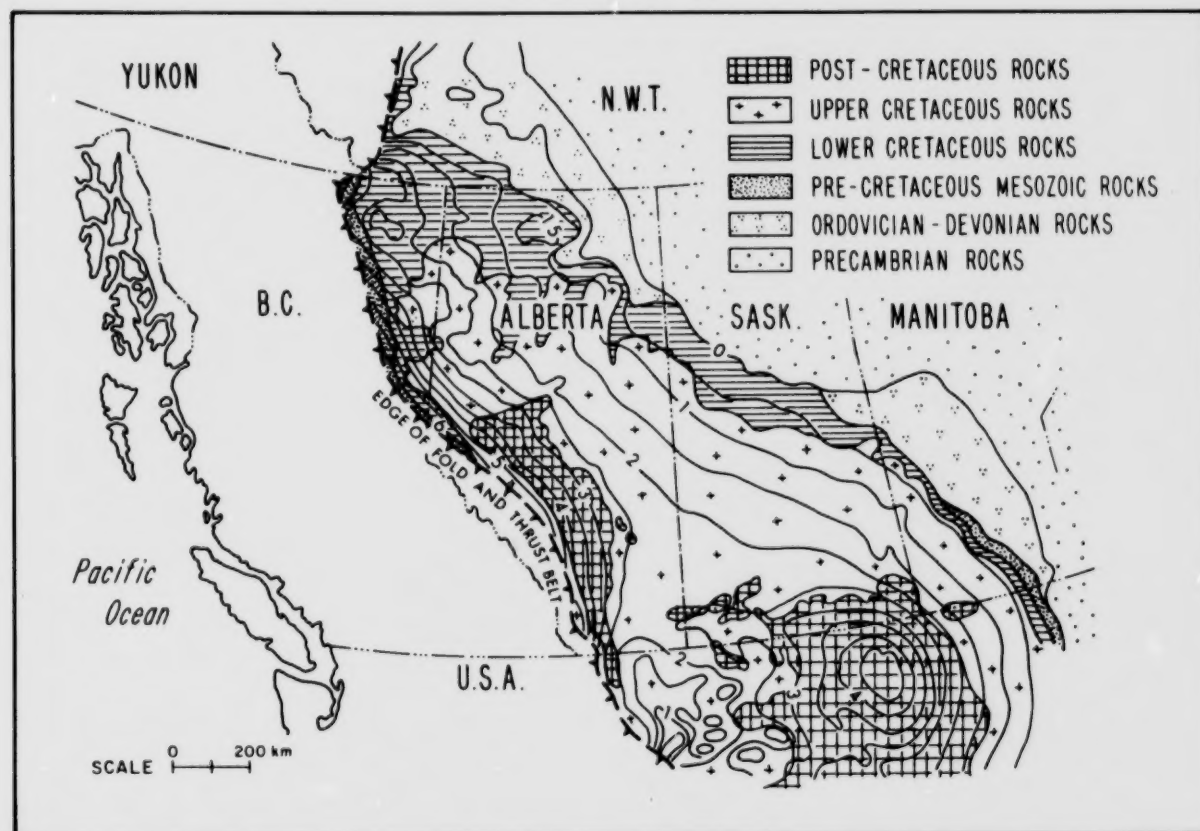


Figure 5. Geology of the post-Tertiary or present-day bedrock erosional surface, to illustrate distribution of the Zuni and Tejas sequences. Contours in kilometres (after Porter et al., 1982) show total preserved thickness of Phanerozoic rocks.

of restricted-marine facies in the Williston Basin. This is illustrated exceedingly well by the Saskatchewan succession which includes the anhydrites and vari-coloured shales of the (upper) Watrous Formation, and the similar but more commonly grey shales, and the dolomites, limestones, and sandstones of the Gravelbourg and Shaunavon Formations (Francis, 1956; Klingspor, 1958; Milner and Blakslee, 1958; Wall, 1960; Christopher, 1964, 1966; Paterson, 1968; Brooke and Braun, 1972). By the Late Jurassic Epoch, however, the southern end of the Belt Island-Sweetgrass promontory had been inundated, and more open-marine conditions were established in the Williston Basin. These are revealed by the calcareous shales and limestones of the Vanguard Formation. Pre-Cretaceous erosion truncated the Middle and Upper Jurassic formations in southern Saskatchewan, so that they, together with many Paleozoic carbonate formations, were overstepped by sandstones of the basal Cretaceous Mannville Group (Table 1).

The bulk of the Zuni sequence is occupied by the Cretaceous System, and an appraisal of this system in terms of its structural context, facies patterns, marine cycles, paleoclimatology, foraminiferal and molluscan biostratigraphy, and time-scales and correlations within the Williston Basin is provided by Caldwell (1982). Kauffman (1977, 1984) described the Cretaceous foreland-basin as divisible into four longitudinal sectors, which may be termed the western

foredeep, west-median trough, east-median hinge, and eastern platform (McNeil and Caldwell, 1981). Subsidence of the western foredeep, bounded to the east by the foreland bulge of the basin, is readily explained by tectonic loading within the adjacent fold-thrust belt of the Cordillera. Less easily explained is the even greater subsidence of the west-median trough, however, and Kauffman has suggested it may be related to a drag-effect from shallow subduction of the Pacific plate. The east-median hinge and eastern platform of the basin may be related to isostatic compensation for the tectonic loading of the western margin. Present-day Saskatchewan spans part of the west-median trough, east-median hinge, and eastern platform of the former Western Canadian foreland basin, and these sectors may be distinguished by the changing facies of the Cretaceous rocks across the province. The blanket of sandy deposits that marks the base of the Cretaceous System in Saskatchewan has been well described by Maycock (1967) and Christopher (1974). At higher levels, the facies vary from those of coarse-grained sandstones in prominent clastic wedges, best developed within the west-median trough (see, for example, Jones, 1961; McLean, 1971) to chalky shales in thin sheets, best developed on the eastern platform (McNeil and Caldwell, 1981).

The Tejas sequence is reminiscent of the Absaroka sequence in the Williston Basin in that it is poorly represented and the remnants are unconformity-bound. These remnants take the

form of thin sheets of gravel and sand, some of them semi-lithified to form spectacular conglomerates with well rounded phenoclasts of resistant ortho- and meta-quartzites (Gulioy, 1975). The Tejas rocks are best preserved in southwestern Saskatchewan where they form a discontinuous sequence ranging from the Eocene Swift Current Formation, through the Eocene-Oligocene Cypress Hills Formation, to the Miocene Wood Mountain Formation (Table 1). Porter et al (1982) correlated the spread of these gravels with episodes of crustal extension and listric normal faulting in the Cordillera.

Although the distribution and kinds of rocks in the Zuni sequence betray a different regional tectonic setting for the Williston Basin during most of Mesozoic and earliest Tertiary time, the sequence accords well with Vail et al's (1977) reconstruction of fluctuation in global sea level. The inferred rise in sea level through the Middle and Late Jurassic Epochs would explain the increasingly open-marine character of the Jurassic rocks in the basin, and the sub-Cretaceous unconformity may be an expression of the sharp fall in sea level, at the end of the latter epoch, which terminates the Jurassic second-order cycle. Progressive rise in global sea level to a high stand near the end of the Early Cretaceous Epoch and renewed rise to the highest stand of all of post-Paleozoic time near the end of the Late Cretaceous Epoch are entirely consonant with the character and distribution of marine Cretaceous rocks in the basin. The Early Cretaceous (Albian) high stand would correlate with the transgressive peak of the Kiowa-Skull Creek marine cycle, represented in Saskatchewan by the widespread deposits of the Joli Fou and equivalent formations, and the Late Cretaceous (Santonian-Campanian) high stand would correlate with the peak of the Niobrara marine cycle, represented in Saskatchewan by the terminal deposits of the Niobrara Calcareous Shale or Upper White-Speckled Shale Formation. According to Kauffman's (1967) model of a Cretaceous marine cycle, the most calcareous deposits accumulated farthest from shore at the transgressive peak, and the most calcareous deposits of the entire Cretaceous section in Saskatchewan are the pale-coloured, chalky shales of the upper Niobrara Formation in the eastern plains (McNeil and Caldwell, 1981). The projected drop in global sea level at the end of the Cretaceous Period would correspond to the onset of non-marine deposition in the Williston Basin, marked in Saskatchewan by the thin upper Eastend, Whitemud, Battle, and Frenchman Formations (Table 1). The two second-order eustatic cycles of the Cretaceous Period, portrayed in the Vail graph, thus seem to be fairly well represented in the Williston Basin. Five third-order cycles also may be represented by the five major transgressive-regressive marine cycles discussed by Caldwell (1982), although some apparent variation in the timing of the transgressive peaks and regressive troughs leaves doubt as to whether these cycles were controlled, or simply influenced in more or less degree, by tectono-eustatic events.

CONCLUSIONS — PRESENT STATUS AND FUTURE THINKING

The wedge of sedimentary rocks which underlies the southern two-thirds of Saskatchewan forms most of the northwestern segment of the Williston Basin and offers stratigraphic evidence critical to reconstructing the history of this archetypal North American, intracratonic depression. The wedge may be resolved into a series of stratigraphic sequences, separated by

unconformities. These sequences conform to the Sauk, Tippecanoe, Kaskaskia, Absaroka, Zuni, and Tejas epicratonic sequences of Sloss (1963), which may be traced with their bounding unconformities throughout much of the Stable Interior of the continent. Agreement between, respectively, the time-spans of deposition and erosion and those of the higher and lower fluctuations of global sea level in the second-order cycles of Vail et al (1977) is close — so close, indeed, as to warrant the conclusion that the major transgressive-regressive marine cycles, which controlled deposition within the Williston Basin, were themselves controlled by eustasy. Whereas the history of the basin is quite well understood, the origin of the basin and of the arches that bound it peripherally is problematic and remains one of the most fundamental unresolved questions of cratonic geology.

Phanerozoic sedimentary rocks in Saskatchewan also form the east-median segment of the Western Canadian Basin. Dependent on how broadly or narrowly the Williston Basin is defined, it forms a greater- or lesser-sized structural element on the flank of the encompassing Western Canadian Basin, and the two basins overlap more extensively within Saskatchewan than within any other province or state. Unlike the Williston Basin, the origin of the Western Canadian Basin, seems reasonably clear. It is a continental-margin basin, initially resulting from stretching and rifting at the western edge of the North American lithospheric plate, and it remained a marginal basin (although not always a divergent one) until a collage of displaced or exotic terranes became accreted to the western margin of North America at a much later stage in the basin's history. Collision of two of these terranes began eastward displacement onto the Craton of the pile of supracrustal rocks that had accumulated from Proterozoic time onwards, and this displacement culminated in the building and uplift of the fold-thrust belt of the Rocky Mountains in later Mesozoic and early Cenozoic times. When the Rocky Mountains were being built, the Western Canadian Basin became transformed into a foreland basin, a trap for the vast quantities of detritus eroded from the orogen.

The Sauk, Tippecanoe, Kaskaskia, and Absaroka sequences in Saskatchewan, collectively Middle Cambrian to (probably) Middle Triassic in age, mark the long platform phase of the Western Canadian Basin. After deposition of the terrigenous clastic sediments of the Sauk sequence on the deeply eroded Precambrian Craton, the region now represented by Saskatchewan lay well inboard of the continental margin and was protected by some of the uplifts around the Williston Basin; as a result carbonate sediments were deposited, and these now form the bulk of the Tippecanoe, Kaskaskia, and Absaroka sequences. The Zuni and Tejas sequences in Saskatchewan, collectively Middle Jurassic to Miocene in age, mark the shorter foreland basin phase of the Western Canadian Basin, and the terrigenous clastic sediments which dominate these sequences all across Saskatchewan and beyond attest to the quantity and range of dispersal of sediments stripped by erosion from the growing mountains.

Clearly the history of the Western Canadian Basin is intimately bound to the history of the Western Canadian Cordillera, and an understanding of both calls for an appreciation of global and regional tectonic processes. The Williston Basin is one of a number of secondary structural elements within the Western Canadian Basin — one the independence of which is asserted by its post-dating the initiation of growth of the basin that encompasses it, but one that remains enigmatic so far as the

processes that created it and ensured its longevity are concerned. Subsidence of the Williston Basin may be continuing today: isopach maps of some Cretaceous formations reveal heavier sedimentation within the basin than over the surrounding platform (Williams and Burk, 1964); changes in facies and variations in thickness of several Cretaceous formations suggest uplift along the bounding arches (Stelck, 1975); structure-contour maps on the top of the Niobrara Calcareous Shale or Upper White Speckled Shale point to post-Campanian subsidence of the basin and uplift of certain domes (Bowdoin, Kevin-Sunburst) within it (Williams and Burk, 1964); and the configuration of the eroded remnants of the latest Zuni and the Tejas rocks hint at stronger subsidence within the Williston Basin than within adjoining parts of the Western Canadian foreland basin, with a continuation essentially to Holocene times (Fig. 5). The processes that have governed the creation and continued subsidence of the Williston Basin through the greater part of Phanerozoic time may yet be shown to be tied to global tectonic processes. Be that as it may, the Phanerozoic sedimentary wedge in Saskatchewan is an integral part of both Western Canadian and Williston Basins and cannot be viewed in isolation either stratigraphically or structurally.

A persistent theme of this review has been that the forces which controlled the deposition and erosion of the Phanerozoic rocks in Saskatchewan may be linked through regional tectonic processes. Quite apart from the forces that created the basin of which the Saskatchewan sedimentary wedge is a part, the link is perhaps most strongly manifest in the correlation of episodes of deposition and erosion with episodes of high stand and low stand in the Phanerozoic fluctuations of global sea level. If that correlation does indeed imply eustatic control, then the control may be extended to episodes of growth and foundering of the mid-ocean ridges and to rates of sea-floor spreading.

Modern global tectonic theories are, on the one hand, immediately persuasive and satisfying; on the other hand, very much open-ended and replete with a challenge to solve problems, some new, others old but now clothed in a different garb. Most geologists today are dedicated adherents of at least the main thrust of the new theories, and an evident effect of this has been increasingly, through the past twenty years, to engender in these scientists a much broader and more synthetic way of thinking. Different approaches to the solution of problems now are being taken by the great majority of geologists, regardless of their specialization, but by none more than those who seek better explanation for the genesis and emplacement of natural resources of economic value. Saskatchewan is richly endowed with a remarkable variety of such resources, as other papers in this volume make clear. Resolving the problems posed not only by the sedimentary basins that lie in part within Saskatchewan but also by the hydrocarbon and mineral resources that these basins contain demands now, as it will additionally in the future, more of the new kind of synthetic thinking focused locally, regionally, and globally.

REFERENCES

- Ahern, J.L., and S.R. Mrkvicka, 1984, A mechanical and thermal model for the evolution of the Williston Basin: *Tectonics*, v. 3, p. 79-102.
- Bally, A.W., P.L. Gordy, and G.A. Stewart, 1966, Structure, seismic data, and orogenic evolution, southern Canadian Rocky Mountains: *Bulletin of Canadian Petroleum Geology*, v. 14, p. 337-381.
- Beaumont, C., 1981, Foreland basins: *Geophysical Journal of the Royal Astronomical Society*, v. 65, p. 291-329.
- Beaumont, C., C.E. Keen, and R. Boutilier, 1982, A comparison of foreland and rift margin sedimentary basins: *Philosophical Transactions of the Royal Society of London, series A*, v. 305, p. 295-317.
- Brindle, J.E., 1960, The faunas of the Lower Paleozoic carbonate rocks in the subsurface of Saskatchewan: Saskatchewan Department of Mineral Resources Report 52, 45 p.
- Brooke, M.M., and W.K. Braun, 1972, Biostratigraphy and microfaunas of the Jurassic System of Saskatchewan: Saskatchewan Department of Mineral Resources Report 161, 83 p.
- Caldwell, W.G.E., 1982, The Cretaceous System in the Williston Basin - a modern appraisal, in J.E. Christopher and J. Kaldi, eds., *Proceedings of the Fourth International Williston Basin Symposium: Saskatchewan Geological Society Special Publication 6*, p. 295-312.
- Caldwell, W.G.E., 1984, Early Cretaceous transgressions and regressions in the southern Interior Plains, in D.F. Stott and D.J. Glass, eds., *The Mesozoic of Middle North America: Canadian Society of Petroleum Geologists Memoir 9*, p. 173-203.
- Christopher, J.E., 1961, Transitional Devonian-Mississippian formations of southern Saskatchewan: Saskatchewan Department of Mineral Resources Report 66, 103 p.
- Christopher, J.E., 1964, The Middle Jurassic Shaunavon Formation of southwestern Saskatchewan: Saskatchewan Department of Mineral Resources Report 95, 95 p.
- Christopher, J.E., 1966, The Middle Jurassic Shaunavon Formation of southwestern Saskatchewan: lithologic descriptions of selected cored sections: Saskatchewan Department of Mineral Resources Report 110, 308 p.
- Christopher, J.E., 1974, The Upper Jurassic Vanguard and Lower Cretaceous Mannville groups of southwestern Saskatchewan: Saskatchewan Department of Mineral Resources Report 151, 349 p.
- Dunn, C.E., 1975, The Upper Devonian Duperow Formation in south-eastern Saskatchewan: Saskatchewan Department of Mineral Resources Report 179, 151 p.
- Dunn, C.E., 1982, Geology of the Middle Devonian Dawson Bay Formation in the Saskatoon potash mining district, Saskatchewan: Saskatchewan Energy and Mines Report 194, 117 p.
- Edie, R.W., 1958, Mississippian sedimentation and oil fields in southeastern Saskatchewan: *American Association of Petroleum Geologists Bulletin*, v. 42, p. 94-126.

- Falvey, D.A., 1974, The development of continental margins in plate tectonic theory: *Australian Petroleum Exploration Association Journal*, v. 14, p. 95-106.
- Fowler, C.M.R., and E.G. Nisbet, 1985, The subsidence of the Williston Basin: *Canadian Journal of Earth Sciences*, v. 22, 408-415.
- Francis, D.R., 1956, Jurassic stratigraphy of the Williston Basin area: Saskatchewan Department of Mineral Resources Report 18, 69 p.
- Fuller, J.G.C.M., 1956, Mississippian rocks and oilfields in southeastern Saskatchewan: Saskatchewan Department of Mineral Resources Report 19, 72 p.
- Fuller, J.G.C.M., 1961, Ordovician and contiguous formations in North Dakota, South Dakota, Montana, and adjoining areas of Canada and the United States: *American Association of Petroleum Geologists Bulletin*, v.45, p. 1334-1363.
- Fuller, J.G.C.M., and J.W. Porter, 1962, Cambrian, Ordovician, and Silurian formations of the northern Great Plains, and their regional connections: *Journal of the Alberta Society of Petroleum Geologists*, v. 10, p. 455-485.
- Fuzesy, L.M., 1960, Correlation and subcrops of the Mississippian strata in southeastern and south-central Saskatchewan: Saskatchewan Department of Mineral Resources Report 51, 63 p.
- Fuzesy, L.M., 1966, Geology of the Frobisher-Alida Beds, southeastern Saskatchewan: Saskatchewan Department of Mineral Resources Report 104, 59 p.
- Fuzesy, L.M., 1973, The geology of the Mississippian Ratcliffe Beds in south-central Saskatchewan: Saskatchewan Department of Mineral Resources Report 163, 63 p.
- Gerhard, L.C., 1982, Geological evolution and energy resources of the Williston Basin: *UMR* Journal*, no. 3, p. 83-120.
- Guliov, P., 1975, High-silica gravels of the Cypress Hills Formation in southwestern Saskatchewan: Saskatchewan Department of Mineral Resources, Regina, 19 p.
- Hajnal, Z., and C.M.R. Fowler, 1982, The Earth's crust under the Williston Basin in eastern Saskatchewan and western Manitoba, in J.E. Christopher and J. Kaldi, eds., *Proceedings of the Fourth International Williston Basin Symposium*, Saskatchewan Geological Society Special Publication 6, p. 13-18.
- Hajnal, Z., C.M.R. Fowler, R.F. Mereu, E.R. Kanasevich, G.L. Cumming, A.G. Green, and A. Mair, 1984, An initial analysis of the Earth's crust under the Williston Basin; 1979 CO-CRUST experiment: *Journal of Geophysical Research*, v. 89, p. 9381-9400.
- Haxby, W.F., D.L. Turcotte, and J.M. Bird, 1976, Thermal and mechanical evolution of the Michigan Basin: *Tectonophysics*, v. 36, p. 57-75.
- Holter, M.E., 1969, The Middle Devonian Prairie Evaporite of Saskatchewan: Saskatchewan Department of Mineral Resources Report 123, 133 p.
- Jamieson, E.R., 1979, Well data and lithologic descriptions of the Interlake Group (Silurian) in southern Saskatchewan: Saskatchewan Department of Mineral Resources Report 139, 67 p.
- Jones, H.L., 1961, The Viking Formation in southwestern Saskatchewan: Saskatchewan Department of Mineral Resources Report 65, 80 p.
- Jones, H.L., 1965, The Middle Devonian Winnipegosis Formation of Saskatchewan: Saskatchewan Department of Mineral Resources Report 98, 101 p.
- Kauffman, E.G., 1967, Coloradoan macro-invertebrate assemblages, central Western Interior, in *Paleoenvironments of the Cretaceous Seaway in the Western Interior*: Colorado School of Mines, Golden, and Geological Society of America, p. 67-143.
- Kauffman, E.G., 1977, Geological and biological overview, Western Interior Cretaceous basin: *Mountain Geologist*, v. 14, p. 75-99.
- Kauffman, E.G., 1984, Paleobiogeography and evolutionary response dynamic in the Cretaceous Western Interior Seaway of North America, in G.E.G. Westermann, ed., *Jurassic-Cretaceous Biochronology and Paleogeography of North America*: Geological Association of Canada Special Paper 27, p. 273-306.
- Kay, M., 1951, Geosynclines: *Geological Society of America Memoir* 48, 143 p.
- Kent, D.M., 1960, The evaporites of the Upper Ordovician strata in the northern part of the Williston Basin: Saskatchewan Department of Mineral Resources Report 46, 46 p.
- Kent, D.M., 1963, The stratigraphy of the Upper Devonian Saskatchewan Group of southwestern Saskatchewan: Saskatchewan Department of Mineral Resources Report 73, 51 p.
- Kent, D.M., 1968, The geology of the Upper Devonian Saskatchewan Group and equivalent rocks in western Saskatchewan and adjacent areas: Saskatchewan Department of Mineral Resources Report 99, 224 p.
- Kent, D.M., 1974, A stratigraphic and sedimentologic analysis of the Mississippian Madison Formation in southwestern Saskatchewan: Saskatchewan Department of Mineral Resources Report 141, 85 p.
- Kents, P., 1959, Three Forks and Bakken stratigraphy in west-central Saskatchewan: Saskatchewan Department of Mineral Resources Report 37, 39 p.

* UMR stands for University of Missouri Rolla, but this expansion appears not to be part of the current official name of the publication.

- Klingspor, A.M., 1958, Jurassic stratigraphy of the Sweetgrass Arch-Manitoba section, in A.J. Goodman, ed., *Jurassic and Carboniferous of Western Canada*, John Andrew Allan Memorial Volume: American Association of Petroleum Geologists, Tulsa, p. 27-64.
- Lane, D.M., 1964, Souris River Formation in southern Saskatchewan: Saskatchewan Department of Mineral Resources Report 92, 72 p.
- Macqueen, R.W., and E.W. Bamber, 1968, Stratigraphy and facies relationships of the upper Mississippian Mount Head Formation, Rocky Mountains and Foothills, southwestern Alberta: *Bulletin of Canadian Petroleum Geology*, v. 16, p. 225-287.
- Mallory, W.W., ed., 1972, *Geologic Atlas of the Rocky Mountain Region*: Rocky Mountain Association of Geologists, Denver, 331 p.
- Maycock, I.D., 1967, Mannville Group and associated Lower Cretaceous clastic rocks in southwestern Saskatchewan: Saskatchewan Department of Mineral Resources Report 96, 108 p.
- McCrossan, R.G., and R.P. Glaister, eds., 1964, *Geological History of Western Canada*: Alberta Society of Petroleum Geologists, Calgary, 232 p.
- McLean, J.R., 1971, Stratigraphy of the Upper Cretaceous Judith River Formation in the Canadian Great Plains: Saskatchewan Research Council, Geology Division, Report 11, 96 p.
- McNeil, D.H., and W.G.E. Caldwell, 1981, Cretaceous rocks and their Foraminifera in the Manitoba Escarpment: Geological Association of Canada Special Paper 21, 439 p.
- Meijer Drees, N.C., 1986, Evaporitic deposits of western Canada: Geological Survey of Canada Paper 85-20, 118 p.
- Middleton, M.F., 1980, A model of intracratonic basin formation entailing deep crustal metamorphism: *Geophysical Journal of the Royal Astronomical Society*, v. 62, p.1-14.
- Milner, R.L., and C.W. Blakslee, 1958, Notes on the Jurassic of southwestern Saskatchewan, in A.J. Goodman, ed., *Jurassic and Carboniferous of Western Canada*, John Andrew Allan Memorial Volume: American Association of Petroleum Geologists, Tulsa, p. 65-84.
- Nelson, S.J., 1959a, Arctic Ordovician fauna: an equatorial assemblage?: *Journal of the Alberta Society of Petroleum Geologists*, v. 7, p. 45-47, 53.
- Nelson, S. J., 1959b, Guide fossils of the Red River and Stony Mountain equivalents (Ordovician): *Journal of the Alberta Society of Petroleum Geologists*, v. 7, p. 51-61.
- Nichols, R.A.H., 1970, The petrology and economic geology of the Upper Devonian Birdbear Formation in southeastern Saskatchewan: Saskatchewan Department of Mineral Resources Report 125, 93 p.
- Nisbet, E.G., and C.M.R. Fowler, 1984, A review of some models for the formation of the Williston Basin, in J.A. Lorisong and M.A. Wilson, eds., *Oil and Gas in Saskatchewan*: Saskatchewan Geological Society Special Publication 7, p. 1-3.
- Paterson, D.F., 1968, Jurassic megafossils of Saskatchewan with a note on charophytes: Saskatchewan Department of Mineral Resources Report 120, 135 p.
- Paterson, D.F., 1971, The stratigraphy of the Winnipeg Formation (Ordovician) of Saskatchewan: Saskatchewan Department of Mineral Resources Report 140, 57 p.
- Patterson, J.R., 1961, Ordovician stratigraphy and correlations in North America: *American Association of Petroleum Geologists Bulletin*, v. 45, p. 1364-1377.
- Porter, J.W., 1958, Madison complex in southeastern Saskatchewan-southwestern Manitoba, in A.J. Goodman, ed., *Jurassic and Carboniferous of Western Canada*, John Andrew Allan Memorial Volume: American Association of Petroleum Geologists, Tulsa, p. 364-371.
- Porter, J.W., and J.G.C.M. Fuller, 1959, Lower Paleozoic rocks of northern Williston Basin and adjacent areas: *American Association of Petroleum Geologists Bulletin*, v. 43, p. 124-188.
- Porter, J.W., R.A. Price, and R.G. McCrossan, 1982, The Western Canada Sedimentary Basin: *Philosophical Transactions of the Royal Society of London, Series A*, v. 305, p. 169-192.
- Price, R.A., 1973, Large-scale gravitational flow of supracrustal rocks, southern Canadian Rocky Mountains, in K.A. de Jong and Robert Scholten, eds., *Gravity and Tectonics*: John Wiley and Sons, New York, p. 491-502.
- Reading, H.G., 1982, Sedimentary basins and global tectonics: *Proceedings of the Geologists' Association of London*, v. 93, p. 321-350.
- Sleep, N.H., J.A. Nunn, and L. Chen, 1980, Platform basins: *Annual Review of Earth and Planetary Sciences*, v. 8, p. 17-34.
- Sloss, L.L., 1963, Sequences in the cratonic interior of North America: *Geological Society of America Bulletin*, v. 74, p. 93-113.
- Sloss, L.L., 1982, The Michigan Basin: *UMR Journal*, no. 3, p. 25-30.
- Stelck, C.R., 1975, Basement control of Cretaceous sand sequences in western Canada, in W.G.E. Caldwell, ed., *The Cretaceous System in the Western Interior of North America*: Geological Association of Canada Special Paper 13, p. 427-440.
- Vail, P.R., R.M. Mitchum, Jr., R.G. Todd, J.M. Widmier, S. Thompson III, J.B. Sangree, J.N. Bubbs, and W. G. Hatlelid, 1977, Seismic stratigraphy and global changes of sea level, in C.E. Payton, ed., *Seismic Stratigraphy — Application to Hydrocarbon Exploration*: American Association of Petroleum Geologists Memoir 26, p. 49-212.

- Vail, P.R. and R.M. Mitchum, Jr., 1979, Global cycles of relative changes in sea level from seismic stratigraphy, *in* Geological and Geophysical Investigations of Continental Margins: American Association of Petroleum Geologists Memoir 29, p. 136-149.
- Wall, J.H., 1960, Jurassic microfaunas from Saskatchewan: Saskatchewan Department of Mineral Resources Report 53, 229 p.
- Warren, D.H., and J.M. Healy, 1973, Structure of the crust in the conterminous United States: Tectonophysics, v. 20, p. 203-213.
- Watts, A.B., and M.S. Steckler, 1981, Subsidence and tectonics of Atlantic-type margins: Oceanologica Acta, Supplement to v. 4, p. 143-153.
- Williams, G.D., and C.F. Burk, Jr., 1964, Upper Cretaceous, *in* R.G. McCrossan and R.P. Glaister, eds., Geological History of Western Canada: Alberta Society of Petroleum Geologists, Calgary, p. 169-189.
- Wilson, J.L., 1975, Carbonate Facies in Geologic Time: Springer-Verlag, New York, 382 p.

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GEOLOGICAL ENVIRONMENTS FOR PLATINUM GROUP ELEMENT MINERALIZATION — A BRIEF OVERVIEW

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ABSTRACT

Platinum group element (PGE) mineralization has been found in several different geological environments throughout the world. South Africa, U.S.S.R., U.S.A. and Canada have 70, 14, 14, and 1 per cent respectively of the world's known reserves of PGEs (NYMEX, 1986). The various geological environments in which PGE mineralization has been discovered are considered first globally, then across Canada, and finally at specific localities in Saskatchewan.

INTRODUCTION

Based on past production figures and the nature of the exploited geological environments, PGE deposits fall into three broad categories:

- 1) magmatic sulphide/oxide deposits:
 - a) PGE-Ni-Cu $\pm$ Cr (e.g. Bushveld, Stillwater and Urals), and
 - b) Ni-Cu-PGE (e.g. Noril'sk-Talnakh and Sudbury);
- 2) hydrothermal deposits (e.g. New Rambler and Shinkolobwe); and
- 3) other deposit-types, including placer (e.g. San Juan-Atrato, Tulameen, Goodnews Bay and Nizhnetagil).

Historically, placer deposits have been an important source of PGEs. However, recent exploration activity suggests that the magmatic and hydrothermal environments will be the main exploration targets of the future. For this reason, placer deposits receive only very brief attention in this paper, especially as none has yet been discovered in Saskatchewan.

PGE ENVIRONMENTS — GLOBAL

1. MAGMATIC SULPHIDE/OXIDE DEPOSITS

a) PGE-Ni-Cu $\pm$ Cr deposits are generally referred to as the stratiform or Merensky type. The ores are mined for PGEs, and other metals such as Ni, Cu, Co and Cr are commonly produced as by-products. The best examples of this type of deposit occur in the Bushveld Complex (Republic of South Africa), Stillwater Complex (Montana) and the Great Dyke (Zimbabwe). Stratiform deposits are by far the most important source of PGEs, and the Bushveld and Stillwater Complexes together contain more than eighty per cent of the world's known reserves of these elements.

The host intrusions to stratiform deposits comprise large basaltic bodies which have been emplaced into stable Precambrian continental cratons. Upon cooling, these bodies

develop a layered internal structure due to progressive fractional crystallization of the evolving melt from the floor of the magma chamber towards the roof. The final solidified intrusion usually consists of an ultramafic lower zone and a mafic upper zone. The ultramafic zone is characterized by the crystallization order chromite-olivine-orthopyroxene. A subsequent change in the crystallization order to plagioclase-orthopyroxene and/or olivine gives rise to the plagioclase-rich rocks which make up the remaining portion of the stratigraphic column in the intrusion. As a result of this process, the intrusion consists of a number of lithologically distinct zones with numerous parallel to subparallel cumulate stratigraphic horizons. PGE mineralization in such layered intrusions also has a stratiform character, and consequently may have great lateral extent.

The most notable PGE horizons of this type are the Merensky Reef and the UG2 Chromitite in the Bushveld Complex, and the J-M Reef in the Stillwater Complex. They range in thickness from 10 to 200 cm and contain from 0.1 to 3.0 per cent disseminated sulphides. In the Bushveld Complex, these mineralized horizons have strike lengths exceeding 230 km. In the Stillwater, the J-M Reef extends for 39 of the 48 km strike length of the intrusion. The PGE + Au grade in the Bushveld horizons ranges from 8.1 to 8.7 g/tonne, whereas the average grade for the J-M Reef is 22.3 g/tonne (Naldrett et al, in press).

The Bushveld and Stillwater Complexes, as well as other layered intrusions, have much in common. They have similar crystallization orders, rock types, fractionation trends and mineral deposits. One of the most remarkable likenesses between them is the level at which the PGE mineralization is developed. In both cases, the mineralized zones or intervals occur in plagioclase-rich rocks approximately 500 m above the culmination of the ultramafic (bronzitite) member or zone.

In the Ural Mountains of the Soviet Union and along the west coast of North America, concentrically zoned intrusive complexes (Zoned Alaskan, or Ural type) of the dunite-clinopyroxenite $\pm$ gabbro association are found. In the Urals,

these bodies have produced both in situ and placer platinum deposits. The in situ Pt deposits are confined to irregular chromitite segregations within the core zone of the dunite. In situ concentrations of palladium are confined to sulphide and Fe-Ti-oxide segregations in the gabbros.

b) Ni-Cu-PGE deposits are magmatic sulphide deposits in which the PGEs are by-products of Ni-Cu mining operations. These Ni-Cu dominant deposits have been subdivided by Naldrett (1981) into four groups:

- i) noritic (e.g. Sudbury);
- ii) intrusive equivalents of flood basalts associated with continental rifting (e.g. Noril'sk and Duluth);
- iii) magmatic suites accompanying early stages of formation of Precambrian greenstone belts:
 - a) tholeiitic intrusions (e.g. Lynn Lake and Pechenga), and
 - b) komatiitic lavas and intrusions (e.g. Kambalda and Alexo); and
- iv) tholeiitic intrusions synchronous with orogenies in Phanerozoic orogenic belts (e.g. Rana).

Although low contents of PGEs are associated with all of the above, only groups i and ii contain amounts sufficient to warrant further discussion.

The Sudbury Complex is the only member of group i and is possibly related to a meteorite impact. During the period 1919-56, Canada was the world's leading producer of PGEs, the bulk of which came from Sudbury. The deposit has an average PGE + Au grade of 0.90 g/tonne (Naldrett et al, in press).

The Noril'sk-Talnakh Cu-Ni deposits are located on the northwest margin of the Siberian Platform. These sill-like tholeiitic intrusions were emplaced contemporaneously with, and as feeders to, the Triassic flood basaltic magmatism that gave rise to the Siberian Traps. The mineralized intrusions radiate upward and outward from the Noril'sk-Kharaulakh Fault. The intruded wallrocks include sulphur-rich marine evaporites and sediments which are considered to have contaminated these magmas. The intrusions attain strike lengths of up to 12 km, widths of up to 2 km and thicknesses of 30 to 350 m. They are commonly differentiated from picritic dolerite to gabbro. The disseminated mineralization in the upper portions of the intrusions passes downward into massive ores. The disseminated ores are reported to contain 3.5 g/tonne total PGEs, and the massive ores, 9.7 g/tonne total PGEs (ISMI, research in progress). In 1985, the U.S.S.R. supplied 50 per cent of the market-led economies' Pd requirements, the bulk of which came from these deposits (NYMEX, 1986).

The Duluth Complex is another example of a mafic igneous complex which contains Cu-Ni deposits associated with flood basalt magmatism and continental rifting. This large arcuate intrusive complex is made up of a number of intrusions, and extends for 250 km from Duluth to the Canadian border. The mineralized zone occurs along the western margin of the complex, and is related to crustal contamination of the magma by the underlying sulphide-rich Virginia Formation sediments. Cu-Ni sulphides associated with this complex are enriched in PGEs.

2. HYDROTHERMAL DEPOSITS

To date, the most commonly cited example of an hydrothermal PGE deposit is the New Rambler Mine in the

Medicine Bow Mountains of southeastern Wyoming. The ore occurs as pods in hydrothermally altered and sheared gabbros and diorites. Analyses of 21 samples by McCallum et al (1976) gave average values of 71 ppm Pd, 2.9 ppm Pt and 0.44 ppm Au. The main sulphide phases associated with PGEs are pyrite, chalcopyrite, pyrrhotite, covellite and marcasite.

The lack of well documented hydrothermal PGE deposits may reflect the low number of investigations carried out in this type of environment rather than accurately indicate their frequency or importance.

3. OTHER DEPOSIT TYPES

Platinum group element mineralization is found in environments other than that associated with intrusive complexes. Two of the most striking examples occur in Sri Lanka. At the Mannar tidal flats, presently forming algal mats in the inter-tidal zone are found to contain levels of Pt in the 2050-3294 ppb range. Corresponding Au values range from 486-1100 ppb (Dissanayake and Kristosotakis, 1984). The Muthurajawela peat deposit was found to contain anomalous levels of Pt and Au over thicknesses of 500 cm. One profile disclosed values in the range 956 to 2360 ppb for Pt and 225 to 882 ppb for Au. Values as high as 7897 ppb Pt were encountered.

Anomalous concentrations of Au and PGEs have been found associated with black shales in the Zechstein copper deposits (Kupferschiefer) of Poland (Kucha, 1982). Up to 3000 ppm Au and 1000 ppm Pd have been recorded. Where present, the precious metals are confined to a thin layer (a few centimetres thick) at the base of a black shale which is overlain by phosphates, borates and thucholite-bearing shale.

PGE ENVIRONMENTS — CANADA

Canada is the world's third largest producer of PGEs and, in 1985, supplied the market-led economies with six per cent of each their Pt and their Pd requirements.

Although this country supplies only six per cent of the PGE market, recent exploration for these elements has led to the discovery of some promising new prospects. These and some previously known important PGE occurrences in Canada reveal that geological conditions favourable towards PGE mineralization exist at several intrusive complexes across the country, for example Wellgreen (Yukon Territory); Tulameen (B.C.); Muskox and Rankin (N.W.T.); Nicholson, Rottenstone and Peter Lake (Saskatchewan); Namew, Bird River and Fox River (Manitoba); Big Trout Lake, Lac des Iles, Gordon Lake, Crystal Lake, Marathon, Sudbury, Kanichee and Rathbun Lake (Ontario); and Lac Sheen, Schefferville and Ungava (Quebec).

Approximately 1600 Canadian nickel occurrences are known (GSC CANINDEX FILE). The majority are sub-economic because their mineralization is so low grade. A search of the literature reveals that reference is made to PGEs at approximately 153 Ni occurrences. However, in most descriptions, PGE values were derived from limited assays (pre-1975) on massive sulphides, or PGE presence was quoted as part of more general mineralogical studies.

That sulphide-poor or weakly disseminated-sulphide-bearing mafic and ultramafic rocks are the most favourable potential hosts for significant PGE mineralization cannot be overemphasized. Since the majority of the known Ni-

occurrences in Canada also appear to fall into this weakly mineralized (disseminated) category, they are considered to be excellent exploration targets for PGE mineralization. The large number of such targets and the fact that important PGE mineralization is known to exist in both massive- and disseminated-sulphide-bearing intrusions suggest that the chances are high for further success in PGE exploration.

Review of the known PGE occurrences in Canada shows that excellent examples of all three categories of PGE deposits exist:

1. MAGMATIC SULPHIDE/OXIDE DEPOSITS

a) PGE-Ni-Cu $\pm$ Cr deposits

i) sulphide association:

Merensky type (e.g. Muskox, Fox River, Lac des Iles and Crystal Lake), and

ii) chromite association:

UG2 type (e.g. Bird River and Big Trout Lake), and Zoned Alaskan type (e.g. Tulameen and Polaris);

b) Ni-Cu-PGE deposits

i) noritic (e.g. Sudbury),

ii) flood-basalt-related (e.g. Crystal Lake), and

iii) other (e.g. Wellgreen, Rottenstone, Rankin, Namew, Ungava, Schefferville, Gordon Lake and Muskox);

2. HYDROTHERMAL DEPOSITS (e.g. Rathbun Lake, Nicholson Bay, Peter Lake, and possibly, Kanichee); and

3. PLACER DEPOSITS (e.g. Tulameen and Atlin).

PGE ENVIRONMENTS — SASKATCHEWAN

In terms of grade and variety, Saskatchewan has some of the most spectacular PGE occurrences in Canada, if not the world.

1. MAGMATIC SULPHIDE DEPOSITS

The Rottenstone Ni-Cu-PGE deposit occurs in a granitic migmatite terrain in the Rottenstone Domain of northern Saskatchewan. The host intrusion to the ores is a sill-like harzburgite-orthopyroxenite body which has a strike length of approximately 50 m, a width of 37 to 50 m and a thickness that varies from 8 to 12 m. It dips 30° to the east.

The intrusion is estimated to have had an average grade of 3.28 per cent Ni, 1.83 per cent Cu, 4.70 ppm Pt, 3.90 ppm Pd and 1.03 ppm Au. A metric ton of Rottenstone ore is calculated to have been worth \$267.00 (U.S., 1986) which is more than thrice the value of Merensky Reef ore (\$84.00). In fact, the Rottenstone ores have no parallel in other Ni-Cu-PGE ores described in geological literature. In the vicinity of the Rottenstone Mine is another superficially similar mineralized locality known as the Tremblay-Olson showing. With the exception of their chemistry, these two deposits appear identical. Laboratory investigations of the two deposits have disclosed that they contrast markedly in terms of their Ni and PGE + Au contents and the S/Se ratio of the associated sulphides. The S/Se ratio is particularly helpful towards improving our understanding of the origin of the sulphide mineralization and of why the Rottenstone Mine ores are rich in Ni and PGE + Au whereas the Tremblay-Olson ores are poor in these elements.

With very few exceptions, sulphides of sedimentary origin have extremely low to negligible concentrations of selenium. They contrast markedly with mantle-derived sulphides, which are known to be enriched in selenium. In the Rottenstone Lake area, the syn-sedimentary sulphides have very low contents of Se, and thus high S/Se ratios (average 28,000). The sulphides and associated ores at Rottenstone Mine, however, have high contents of selenium giving rise to low S/Se ratios (average 2500). The only other known magmatic sulphides with similarly low ratios are PGE-enriched, for example those from the Bushveld and Stillwater Complexes. The Tremblay-Olson mineralization has a S/Se ratio of approximately 5500 which is more than twice that found at the Rottenstone Mine. When recalculated to 100 per cent sulphide, the Rottenstone mineralization is approximately eight times as rich in Ni and precious metals as that at the Tremblay-Olson. The only plausible explanation for these differences is that a significant portion of the sulphide mineralization at the Tremblay-Olson showing resulted from crustal contamination of the magma by the surrounding sulphur-rich migmatized sediments.

Examination of mine records and surface samples reveals that approximately fifty per cent of the uneroded portion of the Rottenstone intrusion consisted of sulphides. Such a high proportion of sulphides, for a small intrusion, suggests that the bulk of the sulphides were derived from a much larger magma chamber at depth. Such an environment would be required in order that the sulphides could equilibrate with a large volume of magma from which they could scavenge PGEs and Ni. On the other hand, the patchy nature of the mineralization at the Tremblay-Olson showing and the relatively Ni- and PGE-depleted nature of the sulphides suggest that the parent magma was not sulphide-saturated like that of the Rottenstone deposit. This corroborates the conclusion drawn from the higher S/Se ratios, namely that the Tremblay-Olson mineralization is the result of local contamination.

2. HYDROTHERMAL DEPOSITS

Probably one of the most convincing examples of an hydrothermal PGE-deposit is the Nicholson #2 Zone U-Au-PGE deposit in the Beaverlodge area, northern Saskatchewan.

The oldest rocks in the vicinity of the deposit are dolomite of the Tazin Group and white dolomitic quartzite and red quartzite/quartzite breccia of the Murmac Bay Formation. These sediments were intruded by peridotites and gabbros which make up the Nicholson Bay Ultramafic Complex. The U-Au-PGE mineralization is confined to steeply dipping, carbonate-infilled shears and fracture zones at the contact between the white dolomitic quartzite and the red ferruginous quartzite breccia. The best PGE mineralization occurs in what is known as the #2 Zone, a pitchblende-bearing shear zone juxtaposed with peridotite. The mineralized zone has a minimum strike length of 50 m and a width of 5 to 50 cm. In the past, this zone was evaluated for its uranium potential, and the precious metals were treated merely as "geological curiosities". At least five other U-bearing mineralized zones occur outside the ultramafic complex, and two additional zones very close to the contact.

Recent surface sampling in the vicinity of the #2 Zone has confirmed the existence of exceptional Pt, Pd and Au values. Unfortunately, samples of ore were unobtainable. However, Hawley et al (1953) reported assays from which, with a few extreme values excluded, an average grade of 136 ppm Au, 17.3 ppm Pd, 13.8 ppm Pt and 0.4 ppm Rh was calculated for the #2 Zone. High values of Ag and Bi were also reported.

In an independent study carried out by the author, anomalous PGE concentrations were found only where U-bearing shear zones are in the immediate vicinity of the ultramafic complex. This implies that the PGE mineralization is derived locally from the ultramafic complex. Mineralized zones only 100 metres from the peridotites are not significantly enriched in PGEs. A geochemical and statistical study of samples from the area disclosed no correlation between PGEs and sulphur or arsenic. However, Pt and Pd correlate strongly with uranium ($r=0.91$). This, coupled with ground observations, suggests that additional exploration targets for this type of deposit may be found where airborne radiometric anomalies coincide with intrusive mafic-ultramafic rocks.

3. MAGMATIC/HYDROTHERMAL DEPOSITS

The Peter Lake Complex is a late Archean (Ray and Wanless, 1980) igneous complex made up of a suite of differentiated mafic plutonic rocks ranging in composition from gabbro to diorite with minor ultramafic and anorthositic components. The main mass of the Complex is approximately 200 km long and has a width of 25 to 30 km. It consists of a number of individual intrusions. Significant portions of its western and eastern flanks are made up of sheared equivalents of these gabbros and diorites, the Parker Lake Gneisses, which verge towards the south into the Needle Falls Shear Zone, a major dislocation in the Precambrian of northern Saskatchewan. The axial planar nature of the Needle Falls Shear Zone in relation to the Peter Lake Complex is striking, and strongly suggests that the Shear Zone may have developed along a line of crustal weakness during the late Archean and may have remained active through the Proterozoic.

Petrological, geochemical, structural and metallogenic investigations are presently in progress. The Complex possibly represents late Archean rift-related magmatism, perhaps analogous to the late Proterozoic rift-related magmatism that gave rise to the Duluth Complex. Apart from the Duluth Complex, the Peter Lake Complex is the largest mafic intrusive complex in North America and falls in the "Super Giant" category of mafic intrusions along with the Bushveld Complex and the Great Dyke.

Two types of mineralization have been recognized in the Complex. Magmatic, disseminated, low-grade Cu-Ni mineralization is the older type, and occurs sporadically along the eastern margin. A much younger hydrothermal event, which accompanied the formation of and is geographically confined to north-trending faults (northern expressions of the Tabernor Tectonic Zone), produced some of the best known PGE mineralization in the Complex. Both types of mineralization are found at Ant Lake, 4.2 km west of Patterson Island (Reindeer Lake). Here, disseminated magmatic mineralization seldom exceeds 300 ppb Pt + Pd, but up to 5162 ppb Pt + Pd result from hydrothermal mineralization, which typically shows high Cu and low Ni values. For example, the richest PGE mineralization (5162 ppb) is associated with 8060 ppm Cu and 119 ppm Ni. Such a high Cu/Ni ratio is typical of PGE mineralization in gabbro-hosted hydrothermal deposits such as at New Rambler (McCallum et al, 1976) and Rathbun Lake (Rowell and Edgar, 1986). Its immense size and the presence of significant PGE mineralization together suggest that the Peter Lake Complex has tremendous PGE potential.

CONCLUSIONS

The potential for discovering economically viable occurrences of PGEs in Saskatchewan and in the rest of Canada is high since little exploration for these elements has been done and numerous exploration targets have yet to be examined.

REFERENCES

- Dissanayake, C.B., and K. Kristosotakis, 1984, The geochemistry of Au and Pt in peat and algal mats — a case study from Sri Lanka: *Chemical Geology*, v. 42, p. 61-76.
- Hawley, H., Y. Rimsaite, and T.V. Lord, 1953, Lead bead method of spectrographic analysis of platinum metals, gold, silver and bismuth in sulphide and uranium ores: *Transactions of the Canadian Institute of Mining and Metallurgy*, v. 56, p. 19-26.
- ISMI, 1986, International strategic minerals inventory summary report — platinum group elements: United States Geological Survey Circular 930.
- Kucha, H., 1982, Platinum-group metals in the Zechstein copper deposits, Poland: *Economic Geology*, v. 77, p. 1578-1591.
- McCallum, M.E., R.R. Loucks, R.R. Carlson, E.F. Cooley and T.A. Doerge, 1976, Platinum metals associated with hydrothermal copper ores of the New Rambler Mine, Medicine Bow Mountains, Wyoming: *Economic Geology*, v. 71, p. 1429-1450.
- Naldrett, A.J., 1981, Platinum group element deposits — a review, in L.J. Cabri, ed., *Platinum-group Elements: Mineralogy, Geology and Recovery*: Canadian Institute of Mining and Metallurgy Special Volume 23, p. 197-233.
- Naldrett, A.J., G. Cameron, G. von Gruenewaldt, and M.R. Sharpe, in press, The formation of stratiform PGE deposits in layered intrusions, in Reidel, ed., *The Origins of Igneous Layering*: NATO Advanced Workshop Series.
- NYMEX, 1986, Metals in the news: NYMEX platinum futures 1956-86: thirty years and still growing.
- Ray, G.E., and R.K. Wanless, 1980, The age and geological history of the Wollaston, Peter Lake and Rottenstone Domains in northern Saskatchewan: *Canadian Journal of Earth Sciences*, v. 17, p. 333-347.
- Rowell, W.F., and A.D. Edgar, 1986, Platinum-group element mineralization in a hydrothermal Cu-Ni sulphide occurrence, Rathbun Lake, northern Ontario: *Economic Geology*, v. 81, p. 1272-1278.

GOLD MINERALIZATION IN THE FLIN FLON - AMISK LAKE AREA, SASKATCHEWAN

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ABSTRACT

The distribution of gold occurrences in the Flin Flon and Amisk Lake areas indicates a stratigraphic or structural control governing the localization of these deposits. In the Flin Flon area, two generations of gold mineralization are recognized. The early-generation deposits are narrow (less than one metre wide) quartz-sulphide veins that occupy minor northwesterly trending fractures in basalt; these fractures apparently originated during the second recognizable regional deformation (P2) to have affected the host rocks. The late-generation deposits occupy fractures (which formed during the third regionally developed tectonism, P3) around or within the Phantom Lake Pluton in the following settings:

- 1) quartz veins in intensely carbonatized basalt,*
- 2) multiple generations of quartz veining with attendant porphyry-style alteration in the Boot Lake Pluton, and*
- 3) foliated chlorite-carbonate-sericite rock with boudinaged quartz veins in the Phantom Lake Pluton.*

This late style of mineralization and associated alteration appears to be consistent with that generated by a fracture-controlled porphyry system.

In the Amisk Lake area, two types of gold occurrence are recognized:

- 1) gold-quartz-carbonate-sulphide veins within or flanking fault zones, and*
- 2) structurally and stratigraphically controlled zones of disseminated and vein-type sulphide-gold mineralization within extrusive and intrusive rhyolite porphyries.*

Both types of deposit lie within supracrustal rocks, are accompanied by intense alteration haloes, and were formed prior to the major deformation event, P2 (thus suggesting their early epigenetic hydrothermal origin).

INTRODUCTION

The Flin Flon area has had a long, albeit sporadic, history of gold exploration. This paper attempts to integrate the regional geological evolution with the formation of the gold occurrences. Two points are emphasized:

- 1) the significant differences between the metallogeny of the Douglas Lake — Phantom Lake area and that of the Amisk Lake area, and
- 2) what the recognition of these differences might mean to explorationists.

GENERAL GEOLOGY

The Flin Flon belt is composed of Aphebian submarine volcanic and associated sedimentary rocks, the Amisk Group, and overlying immature coarse terrestrial sediments, the Missi Group (Fig. 1). The belt is in gradational contact to the north

with the Kiseynew metasedimentary terrain, and is unconformably overlain to the south by Ordovician limestone. It extends from Wekusko Lake in Manitoba to the Sturgeon-weir River in Saskatchewan.

Stauffer and Mukherjee (1971) recognized three phases of deformation within the Missi Group. Regional metamorphism accompanied the second of these phases (P2), and generally increased in grade from lower greenschist facies in the south to amphibolite facies in the north. The peak of the Hudsonian Orogeny in the Flin Flon area is correlated with the P2 deformation. Two generations of faulting have been recognized, the earlier apparently coeval with P2, the later with the third phase of deformation, P3 (Byers and Dahlstrom, 1954; Byers et al, 1965).

Four generations of igneous intrusions invade the supracrustal rocks (Stauffer, 1974; R.R. MacQuarrie, personal communication). The oldest forms subvolcanic granitic plutons (Cliff Lake Pluton, and, possibly, the Boot Lake Pluton), followed first by a suite of mafic dykes and then by

two generations of felsic plutons, the later of which includes the Reynard, Annabel, Neagle and Phantom Lake Plutons. Recent studies indicate that the Boot Lake Pluton may also be a late intrusion.

Amisk volcanism occurred at 1.88 to 1.89 Ma, and the last intrusive events at 1.82 Ma (R.R. MacQuarrie, unpublished data; Stauffer, 1985).

DOUGLAS LAKE — PHANTOM LAKE AREA STRATIGRAPHY AND STRUCTURE

The stratigraphy in the Douglas Lake area is broadly correlative with that in the Phantom Lake area (Pearson, 1983). In general, massive and pillowed basalts and associated fragmental rocks at the base of the sequence are overlain by dacitic and rhyolitic flows and pyroclastic rocks, then by graphitic argillite with massive sulphides followed by thick, waterlain tuffs.

The volcanic rocks are intruded by several bodies of gabbro and diorite, the Boot Lake and Reynard Lake granitic plutons and the Phantom Lake porphyritic granite.

The rocks throughout the area have north to northwesterly strikes, and moderate to steep westerly dips. They face to the west. The lowermost basalt unit is cut by nearly conformable fractures, some of which contain sulphides or quartz-sulphide veins. Dextral movement of undetermined, but probably small, extent has taken place along these fractures. Northeasterly trending P3 fractures also have a significant amount of normal dextral movement.

GOLD MINERALIZATION

The first of two generations of gold mineralization predates intrusion of the Phantom Lake Pluton, the second postdates this event.

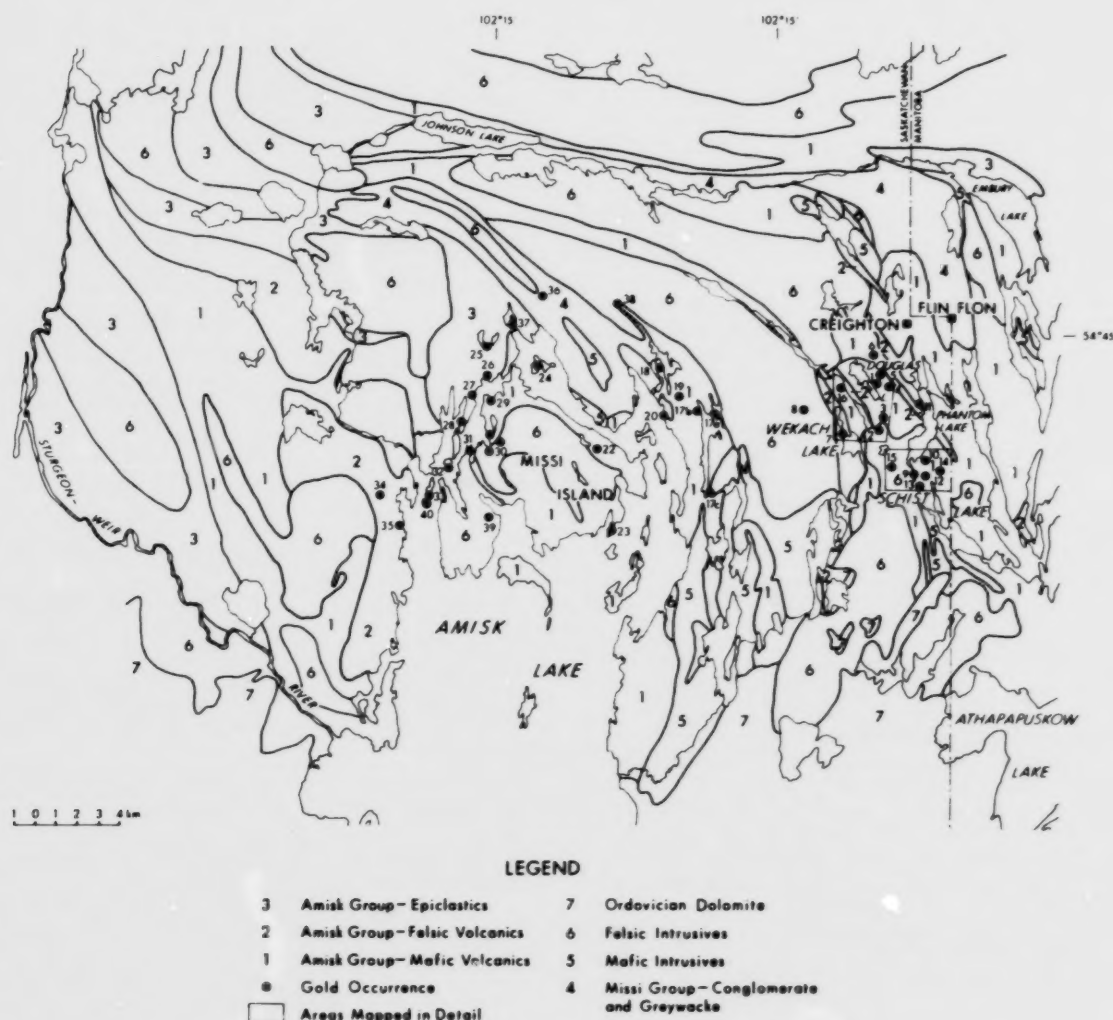


Figure 1. Geology and gold occurrences in the Flin Flon — Amisk Lake area. 1, Newcor Mine; 2, Henning-Maloney Mine; 3, Rio; 4, Unity; 5, Cor; 6, Bomber Lake; 7, Wekach Lake; 8, Angelski; 9, Phantom Lake Mine; 10, MacMillan Mine; 11, North Phantom Lake; 12, Yellow Jacket Group; 13, Phantom-McRobbie Lake; 14, Dee Claims; 15, Boot Lake; 16, Dodo; 17a, Mosher Lake East; 17b, Mosher Lake North; 17c, Mosher Lake South; 18, Mitchell; 19, Sye; 20, Amisk Syndicate; 21, V.M. Group; 22, Derby (Hoodoo); 23, Lucky Strike; 24, Royal; 25, Kent; 26, Duplex; 27, Monarch Mine; 28, Amisk Gold Syndicate; 29, T.C.A.; 30, Laurel; 31, Beaver; 32, Hannay Island; 33, Waverly Island; 34, Wing; 35, Bud; 36, Graham Mine; 37, Golden Cross; 38, Robinson Creek; 39, Ace; 40, Sonora.

The earlier generation (e.g. the Newcor Mine, Cor, Unity and Bomber Lake showings) occurs in the lowermost basalt unit east of Douglas Lake. Narrow (one metre wide) quartz-sulphide veins occupy northwesterly striking fractures. Within the veins, sulphides form massive zones (Newcor), anastomosing stockworks (Cor, Bomber Lake) and vug fillings (Unity, Bomber Lake). In places, they show zonation. Where veins crosscut mafic volcanics, wallrocks are altered to fissile chloritic schist or chlorite-plagioclase-epidote schist. Where quartz-porphyritic rhyolite is transected, as at the Unity occurrence, wallrock alteration is marked by development of chlorite and sulphides on foliation planes.

Mineralization that postdates the Phantom Lake Granite is of three main types:

- 1) volcanic-hosted, carbonate-quartz-sulphide zones (Rio, MacMillan, Dee, Wekach Lake),
- 2) fracture-controlled quartz-sulphide veins in the Boot Lake Pluton (Phantom Lake Mine, Henning-Maloney Mine, Yellow Jacket), and
- 3) fracture-controlled disseminated sulphide zones in the Phantom Lake Pluton (IMC).

The Rio deposit (Pearson, 1984; Middleton, 1985), representative of the volcanic-hosted mineralization, lies on the Rio Fault (Fig. 2). The hanging (northwestern) wall of the fault comprises basaltic lavas and fragmental rocks and the footwall, rocks of the Boot Lake Pluton and its basaltic inclusions. Northeast of the deposit, little alteration has affected rocks along the fault, and shear planes are coated with chlorite and ankerite. To the southwest, however, the fault is marked by a zone of intense ankeritization, silicification and quartz veining. The Rio deposit occurs in a 90-m-wide zone of carbonate-quartz alteration elongated along the trace of the fault, especially where included basalts are in contact with basaltic rocks in the hanging wall. Within this alteration envelope, the fault appears to be represented by a wide zone of fracturing, rather than by a distinct fault plane.

The hanging-wall orebody is a poorly defined zone of pyrite-gold mineralization grading two to four g/t Au in which gold values vary sympathetically with pyrite concentration. Mineralization is commonly concentrated along fractures trending at 170°. The footwall orebody is of considerably higher grade (10 to 20 g/t Au) and comprises narrow (30 to 50 cm wide), massive, pyrite and quartz-pyrite veins striking at 170°.

Type 2 gold mineralization is represented by discrete gold-quartz-copper-tungsten-molybdenite veins in the Boot Lake Pluton (Galley and Franklin, 1985; Pearson et al, 1986). At the Phantom Lake Mine, mineralization is hosted by medium-grained hornblende granodiorite (Fig. 3). The granodiorite and adjacent porphyritic Phantom Lake Granite are crosscut by two sets of planar fractures, the older striking west-northwest and north-northwest, the younger east-northeast and north-northeast. Vein orientation is controlled by the older set of fractures, but the mineralized veins appear not to cross the contact with the Phantom Lake Granite. Pyrite with minor chalcopryite, arsenopyrite, sphalerite and molybdenite, and accessory feldspar and purple fluorite occur in the veins.

Type 2 mineralization is also found as a vein stockwork in a ten-m-wide zone striking parallel to the west-northwest fracture set. Quartz-feldspar veins are crosscut by thinner

quartz-chalcopryite-pyrite veins which are in turn cut by even thinner quartz-chalcopryite veins. Low-temperature alteration assemblages, consisting of epidote, pyrite, quartz and hematite, overprint the mineralization, their location controlled by the north-northeast/east-northeast fracture set.

Type 3 mineralization is characterized by the IMC occurrence north of Boot Lake. Mineralization and associated alteration are spatially controlled by northwest and east-northeast trending shears within the Phantom Lake Granite. Along the shears, one- to three-m-wide zones of strongly foliated chlorite-carbonate-sericite rocks contain boudinaged quartz veins. The foliated rocks bear disseminated pyrite, chalcopryite and scheelite, and the veins, pyrite and scheelite.

AMISK LAKE AREA

STRATIGRAPHY AND STRUCTURE

Interpretation of the stratigraphy in the Amisk Lake area is complicated by the lack of a distinct marker horizon, by the transition from a subaqueous to subaerial depositional environment, and by complex tectonics (Fig. 1). The lower part of the 'Amisk Volcano' comprises submarine basalts and associated breccias and fragmental rocks several thousand metres in thickness (Byers and Dahlstrom, 1954; Longierau, 1980; Ayres, 1977; Ayres et al, 1981; McDougall et al, 1979; Parslow and Gaskarth, 1984; Fox, 1976; Walker and Watters, 1982; Van Wagoner and Van Wagoner, 1981) overlain by tuffs mixed with subaerial and subaqueous flows and by a conglomerate and turbidite sequence. A body of Missi conglomerate and sandstone occupies the northeast Amisk Lake area.

These rocks are folded by second deformation (P2) structures with northerly trending axial planes, and are disrupted by coeval north- to northwest-trending faults (Mosher Lake, Macdonald Creek, West Channel) which show a tendency to branch.

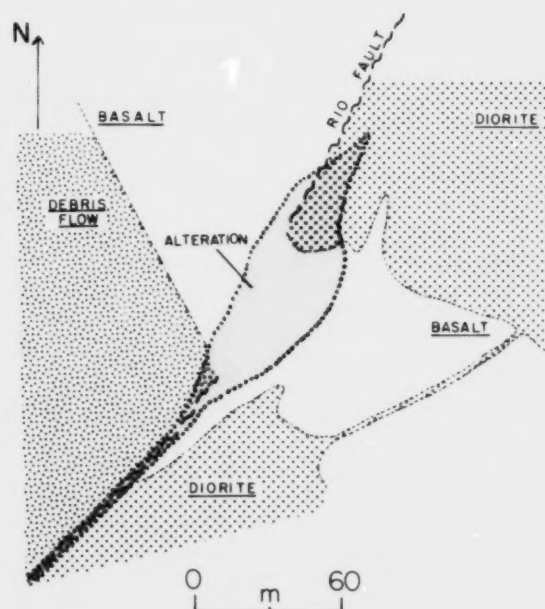


Figure 2. Sketch map of the geology in the vicinity of the Rio deposit.

GOLD MINERALIZATION

Two types of gold deposits are recognized:

- 1) gold-quartz-carbonate-sulphide veins (Amisk Syndicate, Mosher Lake, Mitchell, Sye, Robinson Creek, Graham, Golden Cross, Duplex, Kent, Monarch Mine, Waverly, Sonora); and
- 2) disseminated gold-sulphide zones (Laurel Lake, Gull Island, Beaver and Amisk Gold Syndicate) (Pearson, 1980, 1983).

Type 1 deposits, the gold-quartz veins, are invariably located along the flanks of major faults, as at the Monarch Mine, Sonora and Robinson Creek, or within minor subsidiary faults, as at the Graham Mine, Duplex and Golden Cross. Deposits occur variously within Amisk Group and Missi Group rocks. Despite the wide variety of host rocks, the associated alteration is remarkably consistent, typified by development of pervasive iron carbonate and fine-grained silica-sericite-tourmaline assemblages. In the most intensely altered zones (Sye, Mosher Lake South, Robinson Creek-

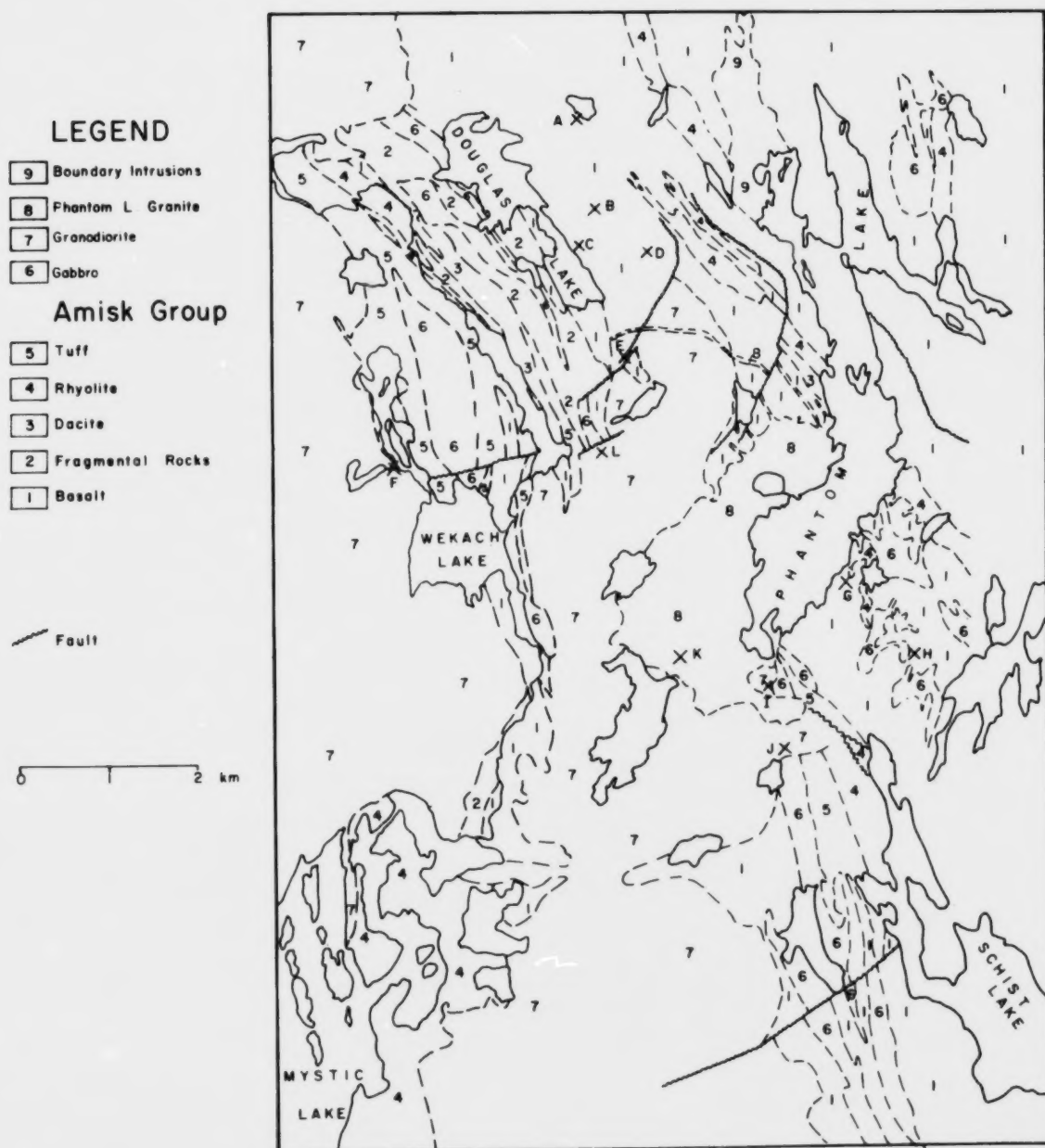


Figure 3. Geology and gold occurrences of the Phantom Lake — Wekach Lake area. A, Bomber Lake; B, Cor; C, Newcor Mine; D, Unity; E, Rio; F, Wekach Lake; G, MacMillan Mine; H, Dee claims; I, Phantom Lake Mine; J, Phantom - McRobbie Lake; K, Boot Lake; L, Henning - Maloney Mine.

Bleiler zone [Pearson, 1982, 1983]), the host basalts have been altered to a very fine-grained, fissile, grey carbonate-chert rock over widths ranging from 2 to 30 m, and fractures are filled with quartz and quartz-carbonate veins.

The two deposits in the Missi Group (Robinson Creek, Graham) are typical gold-quartz-carbonate vein systems developed in proximity to major faults (Pearson, 1982, 1983). Veins are folded by second-phase structures, suggesting that the main period of gold-quartz vein formation was coeval with or postdated faulting but predated the major second-phase folding.

Type 2 deposits occur in the West Channel area of Amisk Lake. Around Laurel Lake and Gull Island (Fig. 4), the lowest part of the stratigraphic sequence is exposed as massive, pillowed and variolitic basalts. These are intruded by massive quartz porphyritic rhyolite which, in the area west of Laurel Lake, is flanked by crystal and lapilli tuffs grading into fine ash tuff. The felsic tuffs are in turn overlain by fine-grained, bedded to laminated mafic tuffs. These rocks are folded by northerly plunging, upright P2 folds with steeply dipping axial surfaces, and are cut by north- and northwest-trending fractures which are subparallel and tangential to the West Channel fault system.

Within this setting, gold occurrences show a variety of accessory minerals. Fractures in basalt and tuff contain thin calcite-quartz-gold $\pm$ pyrite $\pm$ pyrrhotite $\pm$ chalcopyrite $\pm$ sphalerite $\pm$ galena veins, whereas in quartz and quartz-feldspar porphyry the fractures contain disseminated fine-grained pyrite-gold mineralization. Associated with the latter are wide zones of pervasive carbonate and sericite alteration (up to one kilometre wide) with local, more intense, fracture-controlled iron carbonate and sericite alteration, and disseminated magnetite (Pearson, 1981). The mineralization in massive quartz porphyritic rhyolite and associated lapilli tuffs consists of:

- 1) vuggy fractures lined with pyrite-tetrahedrite-tennantite-enargite-gold flanked by successive zones of fine-grained chlorite alteration and sericite alteration, and
- 2) stratabound disseminated pyrite-gold mineralization in which small lenses of sphalerite and green mica are developed, and which is enveloped by a pervasive sericite and iron carbonate alteration and folded by second-phase structures (P2) (see Walker and McDougall, this volume).

DISCUSSION

In the Douglas — Phantom Lake area, early quartz-sulphide vein deposits were emplaced during the formation of second-phase northwesterly trending fractures, prior to intrusion of the Phantom Lake Granite. Veins lie within narrow alteration zones, have similar mineralogy and are commonly vuggy, indicating that they were introduced at rather shallow depths (Boyle, 1979). Brecciated veins in the Unity and Bomber Lake occurrences and the boudinaged nature of the Cor occurrence suggest intermittently active fractures.

The later generation of deposits is more complex. These deposits show differing ore mineralogy, gangue mineralogy, host rock and alteration assemblages, but all postdate the Phantom Lake Granite. They are considered to be genetically associated with a single porphyry system.

Observations made at the Phantom Lake Mine and the IMC deposit suggest progressive alteration, from high to low temperature, along successive generations of fractures. The older fractures trend west-northwest and north-northwest and contain quartz, pyrite, chalcopyrite, arsenopyrite, molybdenite, feldspar and fluorite in addition to chlorite and scheelite. This type of mineralization does not appear to cross the contact of the Phantom Lake Pluton. However, the later east-northeast and northeast fractures containing epidote, pyrite, quartz and hematite cut both the Boot Lake and Phantom Lake Plutons and indicate overprinting of potassic and phyllic alteration by propylitic alteration (Pearson et al, 1986).

Quartz-carbonate veins occur in the Amisk Group rocks in preference to quartz and quartz-feldspar veins. This is not unusual in a porphyry system as variations in vein assemblages appear to be controlled in great part by host rock compositions (Titley, 1982). Each of these deposits (Rio, MacMillan, Dee) is characterized by progressive, fine-grained carbonate and silicic alteration concentric about a fracture zone. The variation in character of this group of gold deposits reflects the nature of the deposition site.

The Amisk Lake gold deposits all occur in extrusive volcanic rocks, subvolcanic intrusives and volcanogenic sediments. In the West Channel area, these rocks were variably fractured subsequent to the formation of the quartz porphyry rhyolite dome (Fig. 4) at Laurel Lake. Alteration minerals are conformable with S_1 fabrics and are deformed by the S_2 axial planar fabric. Although the geometry of individual veins is presently invisible, mineralization is assumed to be contemporaneous with the formation of the alteration assemblages. Hydrothermal fluids probably followed fracture conduits provided within the brittle dacite and rhyolite porphyries, altering and mineralizing them, possibly in a manner similar to that illustrated in Figure 5. They also percolated into the more porous beds within the flanking rhyolitic tuff horizons. The fracture-controlled, base-metal-rich veins in the surrounding basalts and mafic tuffs may have formed from lower temperature, more distal fluids in the same hydrothermal system.

The fracture-controlled gold-quartz veins may also be products of this primary hydrothermal system. This implies

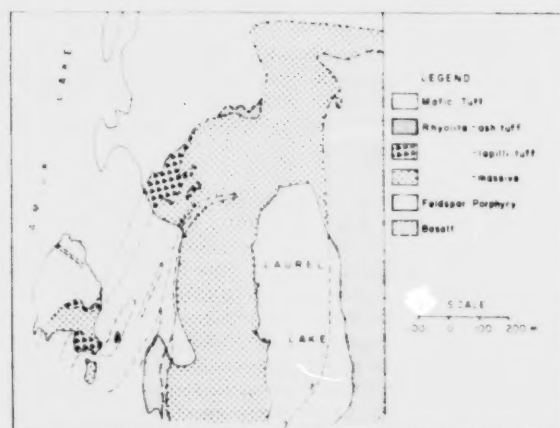


Figure 4. Geological map of the West Channel (Amisk Lake) — Laurel Lake area.

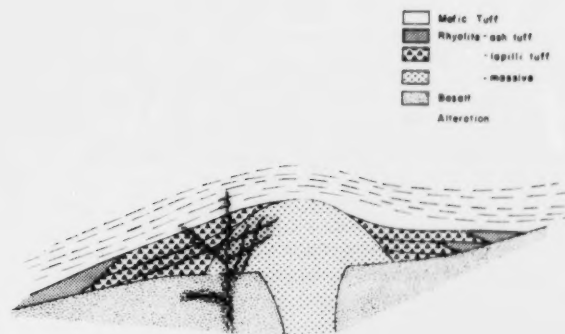


Figure 5. Schematic cross-section to show geological relationships in the West Channel (Amisk Lake) — Laurel Lake area; hydrothermal fluids probably followed fracture conduits, altering host rocks as shown.

that fluids followed the major fracture zones, which formed conduits or channelways and gave rise to the gold-quartz mineralization in response to changing physicochemical conditions. In some deposits (Robinson Creek, Monarch Mine, Amisk Syndicate), the presence of more than one generation of vein formation indicates that the shear zones and hydrothermal activity were active over an extended period of time prior to the second phase deformation (the Hudsonian Orogeny). The major shear zones were probably active during the second phase deformation as well.

CONCLUSIONS

The differences in age, host rock, alteration mineralogy and geological setting indicate a fundamental difference in the genesis of gold deposits in the Douglas Lake — Phantom Lake and Amisk Lake areas.

Most gold deposits in the Douglas Lake — Phantom Lake area postdate the latest intrusive event, emplacement of the Phantom Lake Granite, and were controlled by very late-stage fracturing. The alteration and mineralization assemblages indicate that the deposits were formed by an evolving porphyry system controlled by progressively generated fractures. Gold deposits are present in all rock types including the syn- and post-tectonic (P2, P3 respectively) plutons. The differences between the deposits reflect changes in local geochemical and structural environments. Recognition of various types of alteration assemblages which formed in different host rocks should help explorationists to recognize potential new gold deposits.

Gold deposits and occurrences in the Amisk Lake area were controlled by major fracture systems and other zones of porosity. The presence of quartz and feldspar porphyries is also a favourable criterion. These deposits were apparently formed by a late synvolcanic hydrothermal system: gold mineralization was probably synchronous with the very late stages of volcanism but predated emplacement of the major P2 plutons and peak Hudsonian deformation. Gold deposits in this area are, therefore, most likely to be found in supracrustal and subvolcanic rocks. In this environment, alteration haloes are widespread and, in some cases, quite subtle. Their recognition should assist explorationists to identify new, possibly hidden, deposits.

REFERENCES

- Ayres, L. D., 1977, A transition from subaqueous to subaerial eruptive environments in the middle Precambrian Amisk Group at Amisk Lake, Saskatchewan — a progress report: Centre for Precambrian Studies 1977 Annual Report, University of Manitoba, Winnipeg, p. 36-51.
- Ayres, L.D., N. van Wagoner, and S. van Wagoner, 1981, Physical volcanology of the Amisk Lake volcano, in J.E. Christopher and R. Macdonald, eds., Summary of Investigations 1981, Saskatchewan Geological Survey: Saskatchewan Mineral Resources Miscellaneous Report 81-4, p. 47-51.
- Boyle, R.W., 1979, The geochemistry of gold and its deposits: Geological Survey of Canada Bulletin 280, 584 p.
- Byers, A.R. and C.D.A. Dahlstrom, 1954, Geology and mineral deposits of the Amisk Lake — Wildnest Lake area, Saskatchewan: Saskatchewan Department of Mineral Resources Report 14.
- Byers, A.R., S.J.T. Kirkland, and W.J. Pearson, 1965, Geology and mineral deposits of the the Flin Flon area, Saskatchewan: Saskatchewan Department of Mineral Resources Report 62.
- Fox, J.S., 1976, Some comments on the volcanic stratigraphy and economic potential of the west Amisk Lake area, Saskatchewan: Saskatchewan Research Council Circular 9.
- Galley, A.G., and J.M. Franklin, 1985, Gold-tungsten mineralization associated with the Phantom Lake Granite, Creighton, in R. Macdonald, T.I.I. Sibbald and D.F. Paterson, eds., Summary of Investigations 1985, Saskatchewan Geological Survey: Saskatchewan Energy and Mines Miscellaneous Report 85-4, p. 99-100.
- Longergau, S.J., 1980, Structure and metamorphism of the northeast Amisk Lake area: unpublished M.Sc. thesis, University of Saskatchewan, Saskatoon, 119 p.
- McDougall, F.H., G.R. Parslow, and B.R. Watters, 1979, Flin Flon base metals project, in J.E. Christopher and R. Macdonald, eds., Summary of Investigations 1979, Saskatchewan Geological Survey: Saskatchewan Mineral Resources Miscellaneous Report 79-10, p. 116-119.
- Middleton, T.A., 1985, The relationship between the structural setting and the development of the alteration zone at the Rio Gold Mine, Saskatchewan: unpublished B.Sc. thesis, University of Waterloo, 54 p.
- Parslow, G.R., and J.W. Gaskarth, 1984, Geochemistry of the East Amisk area: Saskatchewan Energy and Mines Open File Report 84-23, 93 p.
- Pearson, J.G., 1980, Flin Flon gold project, in J.E. Christopher and R. Macdonald, eds., Summary of Investigations 1980, Saskatchewan Geological Survey: Saskatchewan Mineral Resources Miscellaneous Report 80-4, p. 70-80.

- Pearson, J.G., 1981, Gold metallogenic studies: Phantom Lake — Schist Lake area, in J.E. Christopher and R. Macdonald, eds., Summary of Investigations 1981, Saskatchewan Geological Survey: Saskatchewan Mineral Resources Miscellaneous Report 81-4, p. 97-100.
- Pearson, J.G., 1982, Gold metallogenic studies: Amisk Lake east area; in R. Macdonald, T.I.I. Sibbald, D.F. Paterson, P. Guliov and J.V. Buller, eds., Summary of Investigations 1982, Saskatchewan Geological Survey: Saskatchewan Energy and Mines Miscellaneous Report 82-4, p. 64-70.
- Pearson, J.G., 1983, Gold metallogenic studies: Flin Flon — Amisk Lake area; in R. Macdonald, T.I.I. Sibbald, D.F. Paterson and P. Guliov, eds., Summary of Investigations 1983, Saskatchewan Geological Survey: Saskatchewan Energy and Mines Miscellaneous Report 83-4, p. 67-74.
- Pearson, J.G., 1984, Gold metallogenic studies: the Rio deposit, in R. Macdonald and T.I.I. Sibbald, eds., Summary of Investigations 1984, Saskatchewan Geological Survey: Saskatchewan Energy and Mines Miscellaneous Report 84-4, p. 123-126.
- Pearson, J.G., F.H. McDougall, and A.G. Galley, 1986, Geology and evolution of gold occurrences in the Flin Flon — Amisk Lake area, Saskatchewan, in L.A. Clark, ed., Gold in the Western Shield: Canadian Institute of Mining and Metallurgy Special Volume 38, p. 399-411.
- Stauffer, M.R., 1974, Geology of the Flin Flon area; a new look at the Sunless City: Geoscience Canada, v. 1, p. 30-35.
- Stauffer, M.R., 1985, Manikewan: an early Proterozoic ocean in central Canada, its igneous history and orogenic closure: Precambrian Research, v. 25, p. 257-281.
- Stauffer, M.R., and A.C. Mukherjee, 1971, Superimposed deformations in the Missi metasedimentary rocks near Flin Flon, Manitoba: Canadian Journal of Earth Sciences, v. 8, p. 217-242.
- Titley, S.R., 1982, The style and progress of mineralization and alteration in porphyry copper systems, in S.R. Titley, ed., Advances in geology of the porphyry copper deposits of southwestern North America: University of Arizona Press, Tucson, Arizona, p. 93-116.
- Van Wagoner, N., and S. van Wagoner, 1981, Shallow water volcanism and sedimentation in a portion of the Flin Flon — Snow Lake greenstone belt, in Centre for Precambrian Studies 1981 Annual Report, University of Manitoba, Winnipeg, p. 71-88.
- Walker, D., and B.R. Watters, 1982, Geochemistry of metavolcanic rocks, Amisk Lake west area, in R. Macdonald, T.I.I. Sibbald, D.F. Paterson, P. Guliov and J.V. Buller, eds., Summary of Investigations 1982, Saskatchewan Geological Survey: Saskatchewan Energy and Mines Miscellaneous Report 82-4, p. 24-30.

GEOLOGY OF THE LAUREL LAKE GOLD-SILVER DEPOSIT

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ABSTRACT

Located on the west side of Missi Island in Amisk Lake, the Laurel Lake deposit lies within an arcuate belt of mafic to felsic metavolcanic rocks and sub-volcanic intrusive rocks flanking the trondhjemitic core of a large volcanic vent complex in the Aphebian Amisk Group.

Regional metamorphism in the deposit area rarely exceeds lower greenschist facies. Polyphase deformation has produced complex fold interference patterns in the metavolcanics, and prominent northeast-, north- and northwest-striking brittle-deformation trends in the more massive intrusive rocks.

The mineralized area around the north end of Laurel Lake is underlain by massive porphyry, which contains large crystals of quartz and feldspar and which possibly represents part of a flow-dome complex with an intrusive core that lies beneath the lake-waters. Immediately northwest of Laurel Lake, the complex passes into an extensive apron of coarse pyroclastic rocks, crystal tuffs and porphyritic flows, all compositionally similar to the massive porphyry. Conformably overlying the fragmental rocks is a thick sequence of finely banded, more mafic tuffs, feldspar crystal tuffs and thin flows.

Mineralization consisting predominantly of pyrite $\pm$ chalcopyrite, tetrahedrite-tennantite, sphalerite and galena occurs within both the massive porphyry and its pyroclastic apron as granular sulphide vein systems, stockworks, disseminations and irregular masses. Ore-grade mineralization occurs within discrete subzones which range in thickness from 1.5 to 7.5 m and which are distinguishable by their dominant ancillary sulphide species. In descending order the subzones are:

- 1) the Pyrite Subzone consisting of disseminations and closely spaced irregular veinlets of granular pyrite,*
- 2) the Tetrahedrite Subzone characterized by at least one per cent of visible dark grey to black tetrahedrite, and by silver to gold ratios of less than 10:1,*
- 3) the Chalcopyrite Subzone containing disseminated pyrite, blebs of tetrahedrite and large irregular masses of chalcopyrite, and*
- 4) the Sphalerite-galena Subzone containing disseminated honey- and red-coloured sphalerite, galena and bluish grey quartz veins; minor visible gold is present within these quartz veins but the majority of the gold apparently occurs as very fine grains and veinlets within the sulphides.*

An extensive alteration halo up to 100 m in width surrounds the mineralized zones in the massive porphyry. The alteration consists primarily of sericitization, bleaching and development of a bright green mica. A pervasive salmon-pink discolouration is visible in the mineralized fragmental rocks and in massive porphyry up to 50 m below its contact with the fragmental rocks. The more mafic tuffs overlying the altered fragmental rocks are extensively carbonatized and locally altered to carbonate-chlorite schist. Recent oxidation in the mineralized area has produced a yellow to red ochrous gossan which in places descends to 50 m vertical depth.

INTRODUCTION

The Laurel Lake gold-silver deposit is situated on the northwest shore of Missi Island in Amisk Lake, Saskatchewan, 25 km southwest of Flin Flon, Manitoba (Fig. 1). It was unrecognized until 1982, although ten gold-bearing quartz-carbonate-sulphide veins and shears, discovered in the early 1930s, occur within a radius of two kilometres of its gossaned outcrops. In 1983, surface mapping and limited

diamond drilling by the Saskatchewan Mining Development Corporation returned high-grade gold values from the vicinity of Baby Gull Island and the adjacent shore of Missi Island. Since the summer of 1984, systematic exploration, principally diamond drilling augmented by surface geochemistry, detailed mapping, and I.P. and resistivity surveys, has resulted in the outlining of an extensive system of alteration and auriferous sulphide mineralization. The system extends in a westerly direction for at least 550 m from the northwest end of Laurel Lake to the east shore of Amisk Lake.

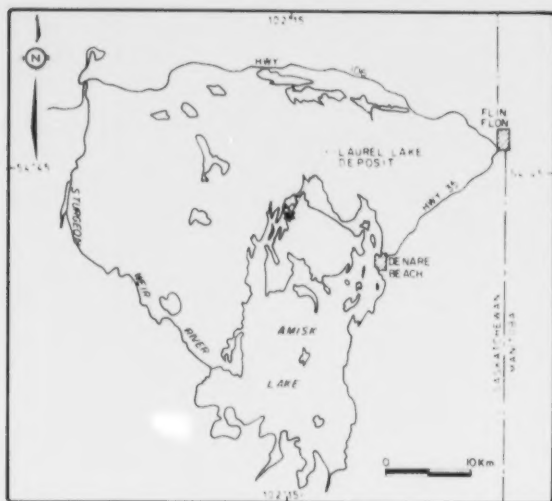


Figure 1. General location map.

During this detailed phase of exploration, the project has been a joint venture with — initially — Hudson Bay Exploration and Development Co. Limited (1984-86) and — currently — Husky Oil. The Saskatchewan Mining Development Corporation acts as project operator.

REGIONAL GEOLOGY

The Amisk Lake area lies at the southeast exposed end of the Flin Flon - Snow Lake Greenstone Belt which in this part of Saskatchewan is composed of a lower, metavolcanic Amisk Group and an upper, metasedimentary Missi Group. Both Groups are of Aphebian age and were named by Bruce (1918) after type localities on Amisk Lake and Missi Island.

The Amisk Group metavolcanics are hosts to the majority of the known base- and precious-metal deposits in the Flin Flon - Amisk Lake area. Compositionally, they range from basaltic to rhyolitic (Byers and Dahlstrom, 1954), have tholeiitic to calc-alkaline affinities (Fox, 1976; Walker and Watters, 1982) and were deposited in subaqueous to subaerial environments (Van Wagoner and Van Wagoner, 1981).

The East Channel area of Amisk Lake (Fig. 2) is underlain by a sequence of massive to well pillowed subaqueous basalts. On the west side of the lake, these basalts are overlain by a sequence of subaerial feldspar-porphyrific dacites. A large wedge of finely bedded turbidites and greywackes, apparent distal equivalents of the dacites, occupies the north and northwest sides of the lake. The contact between these sediments and the underlying East Channel basalts is marked by an extensive graphitic horizon which can be traced around Missi Island beneath the West, North, and East Channels.

Close to, but stratigraphically beneath, this horizon occurs a series of compositionally similar quartz-feldspar porphyritic felsic intrusive bodies. They belong to, and form an incomplete annulus around, the Missi Island intrusive complex which is cored by several nested felsic stocks. The largest of these stocks is a crescent-shaped mass of trondhjemite at the centre of Missi Island. The quartz-feldspar porphyritic intrusives are high-level, subvolcanic rocks which, in several places (e.g. at Laurel Lake), broke surface and gave rise to extensive felsic pyroclastic units.

A large syncline, its core occupied by Missi sediments, has been mapped on the northeast side of Amisk Lake. Here, the rock sequence consists of a thick basal unit of coarse, unsorted, polymictic conglomerate overlain by crossbedded pebbly arkose and by more uniform arkose.

The most striking structural feature of the Amisk Lake area is Missi Island itself, a large, relatively undisturbed area around which the epiclastic, volcanic and sedimentary units are intensely deformed. This feature is best described as a "mega-augen". In the deformed areas, two major fold episodes have been recognized. The earlier episode formed tight, upright, isoclinal folds with a genetically related, strong planar fabric parallel or subparallel to the original bedding planes. The axes of these F1 folds are horizontal and create a circular pattern around Missi Island. Their net effect is to produce large- and small-scale repetition of the stratigraphy. The later episode is marked by more open folds with axial planes trending north to northwest. These F2 structures refold F1 folds to the north and south of Missi Island, and amplify them to the east and west, where their axial planes are parallel. A strong lineation has developed parallel to F2 fold axes.

The final structural event in the Amisk Lake area appears to have been the development of north-, northeast- and northwest-trending brittle faults which produce pronounced topographic lineaments.

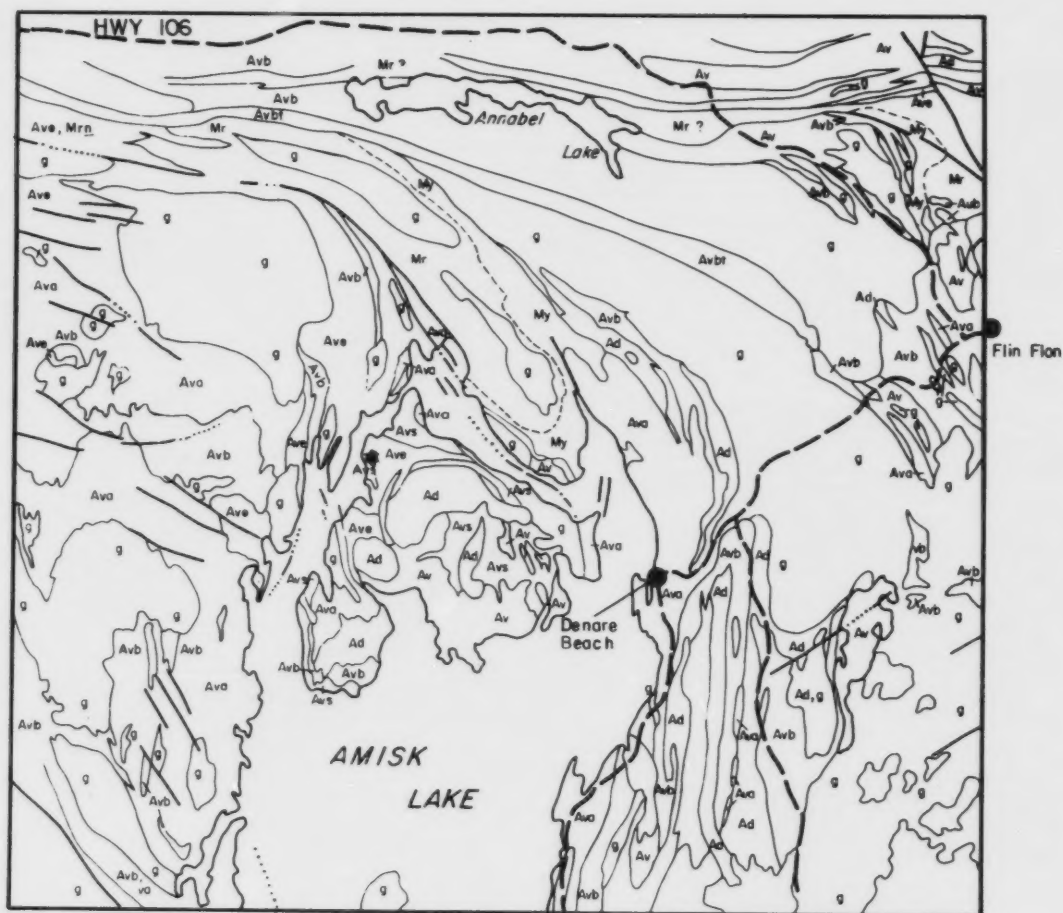
The rocks of the Amisk Lake area are generally of lower greenschist metamorphic grade; within them, many primary volcanic features are well preserved.

LOCAL GEOLOGY

The local geology of the Laurel Lake-Gull Island area is summarized in Figure 3. The massive quartz porphyry stock and its compositionally similar apron of fragmental rocks cropping out between Laurel Lake and the shore of Amisk Lake are geologically and economically most significant. The massive porphyry (actually quartz-feldspar porphyry) generally contains about ten per cent subhedral to anhedral quartz phenocrysts which range in colour from clear white to frosty white to pale opaline blue, and in diameter from 1 mm to more than 10 mm, averaging about 5 mm. Feldspars make up most of the remaining phenocrysts, which are seldom readily recognizable in hand specimen due to destruction of their crystal boundaries during hydrothermal alteration.

The massive, intrusive, root portion of the stock is exposed between Laurel Lake and Amisk Lake. It probably also underlies Laurel Lake to the east and extends south to Hambly Bay, where it apparently interfingers with basalts and dacites into which it was emplaced. Although it does not seem to continue southwards beyond the end of Hambly Bay on surface, deep drill-hole information and the prolongation of an associated magnetic low indicate that it runs down plunge for a considerable distance farther south.

The stock has intruded basaltic volcanic and volcanoclastic rocks which range from massive flows to lapilli tuffs. Locally, a few isolated pillows occur in the basalt flows, which are otherwise generally massive. The massive flows exposed east and northeast of Laurel Lake are dark green in colour, and are full of randomly oriented cooling fractures. In several localities, they contain large vesicles. These massive flows appear to have been unaffected by the two episodes of folding which deform most rocks in the area.



Legend

Supracrustal associations, Flin Flon Domain
(generally lower to upper greenschist facies)

MISSI GROUP

Mr Arkose, graywacke, minor quartz pebble conglomerate and schist.

My Boulder conglomerate

AMISK GROUP

Ave Quartz-feldspar porphyry; feldspathophytic dacite, rhyolite porphyry (mainly intrusive).

Ad Microdiorite, (diorite)

Avb Peridotite, pyroxenite, gabbro, quartz diorite, syenite

Ave Epilastic rocks: fine greywacke, argillite, slate, chert, iron formation, graphitic slate, calcareous shale and chert, quartzite, siliceous shale, interbedded volcanics

Ava Acid to intermediate lavas, flow breccias, pyroclastics; minor basic volcanics, epiclastics and intrusives

Avb Tholeiitic massive, pillowed, brecciated, amygdaloidal, and tuffaceous flows; minor intermediate to acid volcanics, pyroclastics and intrusives.
Avbt-basic volcanoclastic rock

Avu Ultrabasic rocks, undivided

g Granitic rocks, undivided

Symbols

- Highway
- Geological contact
- Fault, shear zone
- Fracture, lineament
- ★ Laurel Lake Deposit



Figure 2. General geology of the Amisk Lake - Annabel Lake area (after Macdonald, 1981).

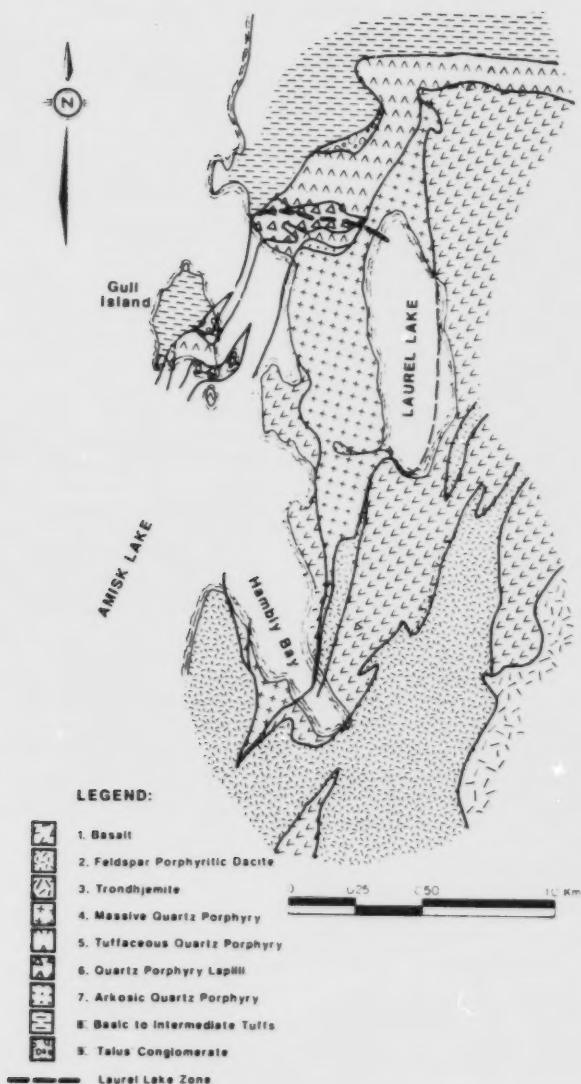


Figure 3. Geology of the Laurel Lake area.

Basic lapilli tuffs appear to overlie the massive basalt flows beneath Laurel Lake, but the stratigraphic relationship of the two rock types is complicated by intrusion of the quartz porphyry stock.

At the northwest end of Laurel Lake, the massive stock is directly overlain by a cap of porphyritic fragmental rocks. From here, the fragmental rocks extend as an apron southwestwards below the waters of Amisk Lake, and through and south of Gull Island. To the northwest, they become finer grained and thinner away from the stock. At its widest point, the volcanoclastic apron appears to be several hundred metres thick. Its contact with the massive stock is complex, with locally developed interfingering between tuffs and quartz-feldspar porphyry dipping 30° to 70° northwestwards.

The porphyry tuff is compositionally the same as the massive stock, but is texturally different. It was probably rapidly

deposited as it is little contaminated or uncontaminated by other volcanic deposits.

Immediately over the stock is a cap consisting of several individually recognizable units, some of which are of limited lateral extent, of fragmental rocks. The basal unit is a sandy-coloured, arkosic-textured, banded tuff which appears to have been waterlain. This unit is known only from a few drill holes located immediately northwest of Laurel Lake and is overlain by a massive, moderately well foliated unit similar to the massive stock except for its planar fabric. This may be a crystal tuff or a flow. Above this massive unit is a thick unit of poorly sorted volcanic conglomerate containing well rounded, lapilli-to bomb-size clasts. The compositions of both clasts and matrix are identical. Consequently, where the unit is unaltered, clast boundaries are difficult to distinguish. This unit is laterally discontinuous. In the vicinity of Gull Island, it occurs at several levels within the succession of volcanoclastic rocks. Northwest of Laurel Lake, the conglomeratic unit is overlain by another thick unit of massive, weakly foliated porphyry which may be a flow or a crystal tuff. Above this porphyry is a discontinuous, fairly well bedded, fine-grained tuff with a strong planar fabric parallel to its bedding planes. At one locality north of Laurel Lake, the massive weakly foliated porphyry unit is directly overlain by a one- to two-metre-thick layer of coarse clasts supported by little or no matrix.

Westwards, along strike from Laurel Lake, the volcanoclastic units of the stock's apron are in abrupt, discordant contact with overlying basic to intermediate tuffs, suggesting that erosion of the apron took place locally prior to deposition of the younger, more basic tuffs.

On Gull Island and in some of the nearby drill holes, the fragmental porphyry contains tuff units devoid of quartz phenocrysts. This may be due to differential settling of the quartz and feldspar phenocrysts during formation of the tuffs.

On the southwest shore of Hambly Bay is a wedge of massive, fragmental porphyry which may have been displaced from the main body by the Hambly Lake Fault.

The fragmental porphyry unit is overlain by basic to intermediate tuffaceous beds which are finely layered to massive. About 0.25 km northwest of Laurel Lake and on the east shore of Gull Island, northeast-striking wedges of this unit contain up to ten per cent porphyry clasts of lapilli-size and larger. These wedges may represent local slump or talus conglomerates.

On Gull Island, the capping tuffaceous units contain a conformable, coarse feldspar porphyry unit which may be a crystal tuff.

In the vicinity of Laurel Lake and Gull Island, rock units from the massive basalts to the basic and intermediate tuffs have been intruded by feldspar-porphyritic dacite dykes and sills which range in texture from fine grained (with only a few small feldspar phenocrysts) to coarse grained (with 80 to 90 per cent feldspar phenocrysts averaging about 10 mm in diameter). The massive porphyry stock contains fewer dykes than its fragmental cap. The dykes near the Laurel Lake Zone strike roughly north-south, dip steeply to the west and crosscut bedding and major rock-unit boundaries at sharp angles. They appear to have been deformed by both folding episodes according to outcrop evidence.

Beneath the north end of Laurel Lake, the massive porphyry stock contains narrow (0.5 to 1.0 m thick), dark green basaltic dykes which are several hundred metres in length, strike north-south and dip shallowly to the west.

STRUCTURE

The massive core of the Laurel Lake stock and the massive flow basalts are relatively undeformed by either of the two fold episodes, and have no well developed, tectonically produced planar fabrics. The fragmental porphyry and the overlying tuffs are deformed to varying degrees by both fold episodes. In the more massive fragmental rocks and close to the massive stock, deformation is limited to non-existent. Away from the shadowing effect of the main stock, the tuffs and lapilli tuffs are intensely deformed by both the F1 and F2 events. The first deformation, F1, caused flattening of large clasts parallel to bedding planes in some localities producing a distinguishable planar fabric (S_1). The second deformation, F2, has folded S_1 into tight crenulations with strong, north-south trending, steep westerly dipping axial planar fabrics (S_2). On a large scale, F2 has generated large Z folds which, over the area of Laurel Lake and Gull Island, have wavelengths of several hundred metres and left-lateral shear zones through their flanks and crests. These shears are visible in small-scale structures. They cause a stepping of fold closures in a southwesterly direction. F2 folds plunge about 45° to the northwest. Elongation of clasts (L_2) occurs in the same direction.

Several sets of late brittle faults cut the Laurel Lake area. Where intersected in drill holes, these fault zones are often one metre or less in width and are filled with a soft weathered gouge. Unlike predeformation fault zones which were sealed, these postdeformation brittle faults are more open and therefore more susceptible to weathering and erosion, producing valleys.

Three main strike directions have been identified for these faults, but their sense of movement is unknown. One set, exemplified by the Hambly Lake Fault which passes through (and helped form) Hambly Bay, trends in a northwesterly direction. A second set trends northeast, and the third set trends due north. The step-like pattern of the western shore of Laurel Lake is controlled by the intersection of the northeast and northwest fault sets.

At several localities (including the Laurel Lake Zone itself), these late faults appear to follow segments of older planes of structural weakness which they may have reactivated.

ALTERATION PATTERNS

Much of the area around the Laurel Lake stock has been affected to some degree by the hydrothermal system that deposited the gold-silver mineralization. The alteration effects are visually and geochemically recognizable.

MAJOR OXIDE ALTERATION PATTERNS

Geochemical analyses of 150 rock samples from the porphyry stock, its fragmental apron and the overlying mafic to intermediate tuff units indicate extensive redistribution and introduction (or loss) of Na_2O , K_2O , CaO and Fe_2O_3 .

Since the porphyry stock and its fragmental cap were originally of fairly uniform composition, depletion and/or enrichment patterns in the alkalis should indicate the intensity of alteration.

The average K_2O and Na_2O contents of the unaltered porphyry appear to have been around 2.75 and 2.95 per cent respectively. The only portion of the stock which has these amounts of K_2O and Na_2O lies between the southwest shore of Laurel Lake and Amisk Lake. The remainder of the porphyry is altered to various degrees, with K_2O enrichment up to 9.75 per cent and Na_2O depletion to 0.25 per cent.

Potash-enrichment patterns expressed as percentage gains (or losses) relative to unaltered porphyry (Fig. 4) show that the most intensely altered areas occur within the fragmental rocks on the southeast corner of Gull Island, in the lapilli tuffs west of the north end of Laurel Lake, and immediately north of Laurel Lake. In the two more northerly areas, the drill-indicated mineralized zones fall within the +150 per cent K_2O -gain contour.

Soda depletion closely mimics K_2O enrichment except towards the upper contact of the fragmental rocks and in the immediately overlying intermediate tuffs, where moderate enrichment (+100 per cent) occurs.

Calcium and iron oxides are generally unaltered to depleted within the main K_2O -enrichment areas in the porphyry and fragmental rocks, but, towards the periphery of these areas and in the overlying tuffs, they show moderate to strong enrichment.

These bulk chemical changes are, in the main K_2O -enriched areas, reflected by the development of abundant sericite, clots of pale green mica, and light to dark salmon-pink colouration. The pervasive pink 'alteration', common within the fragmental rocks but restricted to near-surface sections of mineralized zones in the massive porphyry (see Fig. 6), is probably due to weak hematization. The green mica clots are flattened along S_1 and are folded by F2, suggesting that alteration was predeformational.

Within the mineralized sections of the high- K_2O alteration zones, the sericite takes on a characteristic waxy yellow to yellowish green colour; the more intense the colour, the higher the gold content in the sulphides. Minor amounts of potassium feldspar and tourmaline have been found in quartz veins in intensely altered fragmental rocks on the south end of Gull Island and close to the upper tuff contact west of Laurel Lake.

Calcium and iron enrichment high in the hydrothermal system is visually apparent by the development of moderate amounts of calcite and large amounts of ankerite at the top of the porphyry fragmental rocks and in the overlying intermediate tuffs. This carbonatization is, in places (e.g. on Gull Island), intense enough to obliterate completely the primary rock texture and composition. The upper intermediate tuffs are locally enriched in MgO and K_2O , a feature which facilitated the conversion of the tuffs, where subjected to appropriate pressure-temperature conditions, into chlorite-carbonate-biotite schists. Such schists are particularly well developed along the contact between porphyry fragmental rocks and tuffs immediately north of the north end of Laurel Lake.

TRACE ELEMENT DISTRIBUTION PATTERNS

Gold, Ag, Cu and Zn values from the geochemically analysed rock samples have distribution patterns somewhat similar to those of K_2O and Na_2O .

Gold in the porphyry and fragmental rocks shows enrichment of greater than 500 ppb in all three areas of +150 per cent K_2O -gain (Fig. 4) and, in addition, of greater than 1000 ppb in

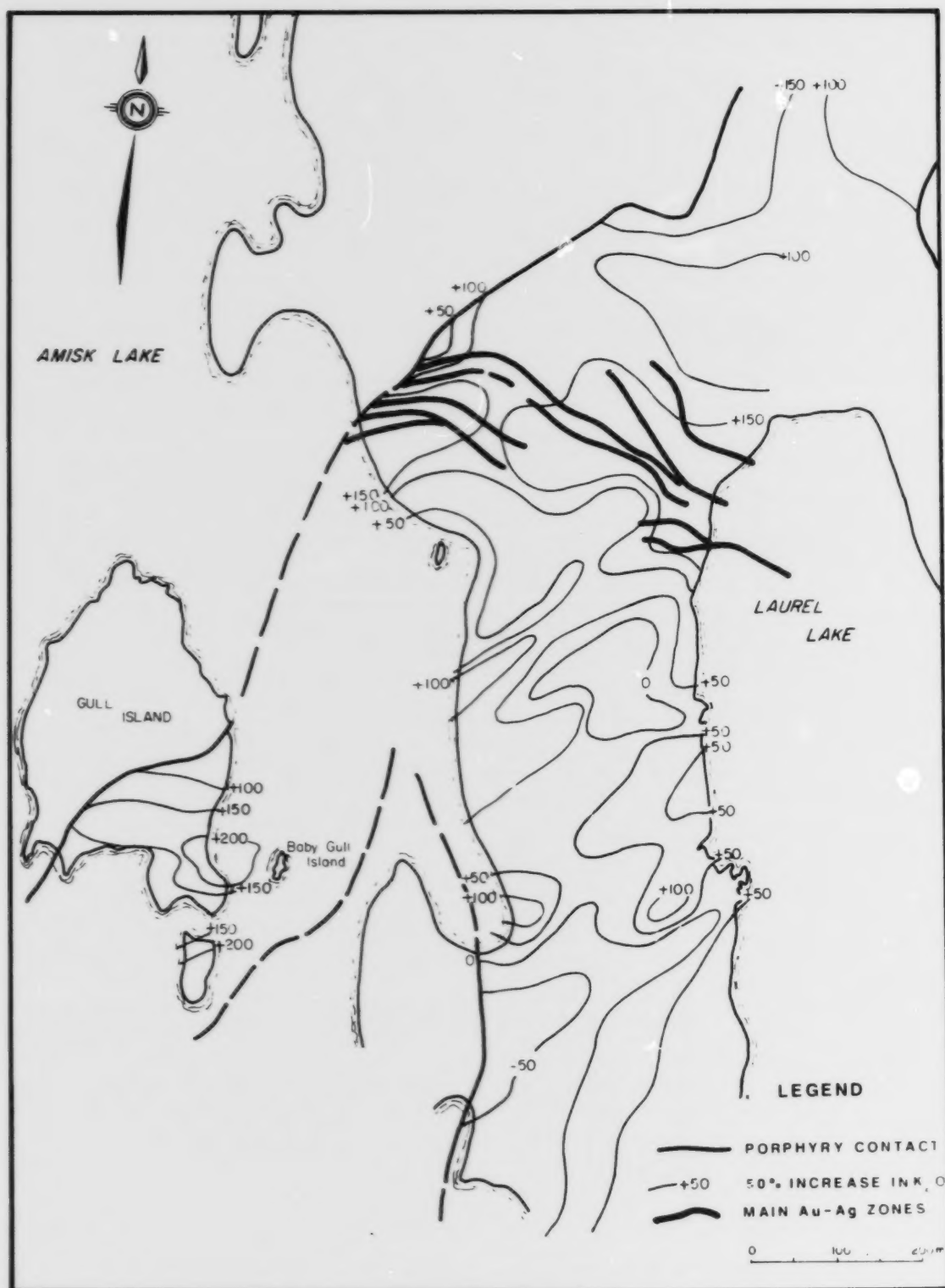


Figure 4. K_2O percentage gains or losses in the Laurel Lake porphyry.

two areas of altered intermediate tuffs north of Laurel Lake (Fig. 5) where K_2O enrichment has also been observed. This juxtaposition of gold- and K_2O -enrichment suggests that hydrothermal activity and mineralization continued after deposition of these tuffs. Silver distribution is similar to that of gold, but is more restricted with only two areas (the northwest side of Laurel Lake and the south end of Gull Island) showing values greater than 5 ppm.

Copper and zinc values are highest in the carbonate-rich sections of the upper porphyry fragmental rocks and overlying intermediate tuffs. Copper enrichment is greater than zinc enrichment in the carbonatized porphyry fragmental rocks, whereas zinc contents are higher than copper contents in carbonatized intermediate tuffs.

Other trace elements, including As, Sb, Pb, Hg, Mo and W, were analysed, but correlatable distribution patterns were not found.

MINERALIZATION

Economic gold and silver mineralization within the Laurel Lake - Gull Island area appears to be of synvolcanic epithermal origin. It is associated with base-metal mineralization to only a minor degree. The precious metals were remobilized and reconcentrated during postvolcanic tectonism but, for the most part, retained their primary distribution pattern.

The broad area of intense alteration in and around the Laurel Lake porphyry stock seems to have been developed by the same hydrothermal system that produced the precious metal mineralization. To date, the best documented area of mineralization is the Laurel Lake Zone.

The Laurel Lake Zone, as presently outlined, lies within a belt of intense sodium depletion and potassium enrichment which extends westwards from the northwest end of Laurel Lake to the east shore of Amisk Lake. Near surface, within the massive porphyry, the Zone is intensely sericitized over a width of several hundred metres, and contains low-grade gold values (0.01 to 0.05 oz. per ton). Within the main Zone, subzones of higher grade mineralization are distinguishable by their dominant associated sulphide types. They are 1 to 7.5 metres in width, strike west-northwest and have dips ranging from 30° north (near the contact between massive porphyry and fragmental rocks) to steeply southwards (beneath Laurel Lake). They are spaced at about thirty-metre intervals and appear to be parallel or subparallel to each other. Studies to date indicate that a subzone of one sulphide type may grade laterally and/or vertically into that of another sulphide type. Figure 6 illustrates in cross-section the general distribution from north to south of the different sulphide subzones within the massive porphyry:

- 1) the Pyrite Subzone,
- 2) the Tetrahedrite Subzone,
- 3) the Chalcopyrite Subzone, and
- 4) the Sphalerite-galena Subzone.

1) The **Pyrite Subzone** consists predominantly of pyrite mineralization varying from massive bands to irregularly distributed stringers and pods. The pyrite is fine, granular and friable, and is possibly silica-encapsulated as even massive sections show little or no conductivity.

2) The **Tetrahedrite Subzone** consists predominantly of tetrahedrite-tennantite-enargite with minor associated coarse-grained pyrite, chalcopyrite and traces of sphalerite. This is the most intensely sericitized of all the subzones. Fine, irregular, grey, sugary quartz veins are also developed in and around the Subzone and may form up to ten per cent of the rock.

3) The **Chalcopyrite Subzone** is dominated by chalcopyrite which occurs as irregular pods and blebs up to 5 cm wide and constituting about ten per cent of the rock. Pyrite is the main accessory mineral and has the same distribution as the chalcopyrite.

4) The **Sphalerite-galena Subzone** is characterized by sugary blue quartz veins which carry ten per cent red sphalerite, and two to three per cent chalcopyrite and galena as irregular veins and clots. The quartz veins are up to 20 cm wide and occur singularly within the Subzone. Several per cent pyrite is finely disseminated in wallrock immediately around the veins. A broad halo of very fine honey-coloured sphalerite brackets the Subzone.

As the mineralized subzones pass into the western extension of the Laurel Lake Zone hosted by fragmental-rock units, they change from distinctive sulphide-enriched bands within the massive porphyry stock into a broad layer of dispersed pyrite mineralization which continues up to the contact between the acidic volcanoclastic rocks and the overlying basic tuffs. The pyrite within this layer occurs as fine disseminations and irregular granular clots forming one to five per cent of the rock.

In the most intensely mineralized portions of the lapilli tuffs, the interclast matrix is composed of green mica, sericite, and granular pyrite. In the finely bedded tuffs, bands of increased pyrite content follow discrete bedding planes, producing layers of pink-red gossan spaced 0.5 to 1.0 m apart across surface exposures.

Base-metal sulphides occur only as small-scale pods and cross-cutting fracture fillings in a few localities within fragmental rocks.

A few discontinuous, irregular, crosscutting remobilized quartz veins also occur in the western extension of the Laurel Lake Zone. They are coarse-grained, white veins containing several per cent pyrite as fine, brass-coloured intergranular laminae.

Where the mineralizing system penetrated the intermediate to basic tuffs overlying the porphyry fragmental rocks (i.e. north of Laurel Lake), a pyrite-rich band formed just above the contact. This band reaches several metres in thickness, and contains up to 30 per cent disseminated pyrite as well as several per cent galena and sphalerite. It extends laterally for several hundred metres. Minor disseminated pyrite accompanies the system's further penetration up into the tuffs.

Other sulphide minerals which occur in minor amounts within mineralized zones in the porphyry are arsenopyrite, molybdenite, and stibnite. They have been seen in drill core at only a few localities, although analysis of a selection of core samples indicates the presence of antimony and arsenic in most of the mineralized subzones.

The distribution of gold and silver varies throughout the Laurel Lake system. Within the sulphide-veined subzones in

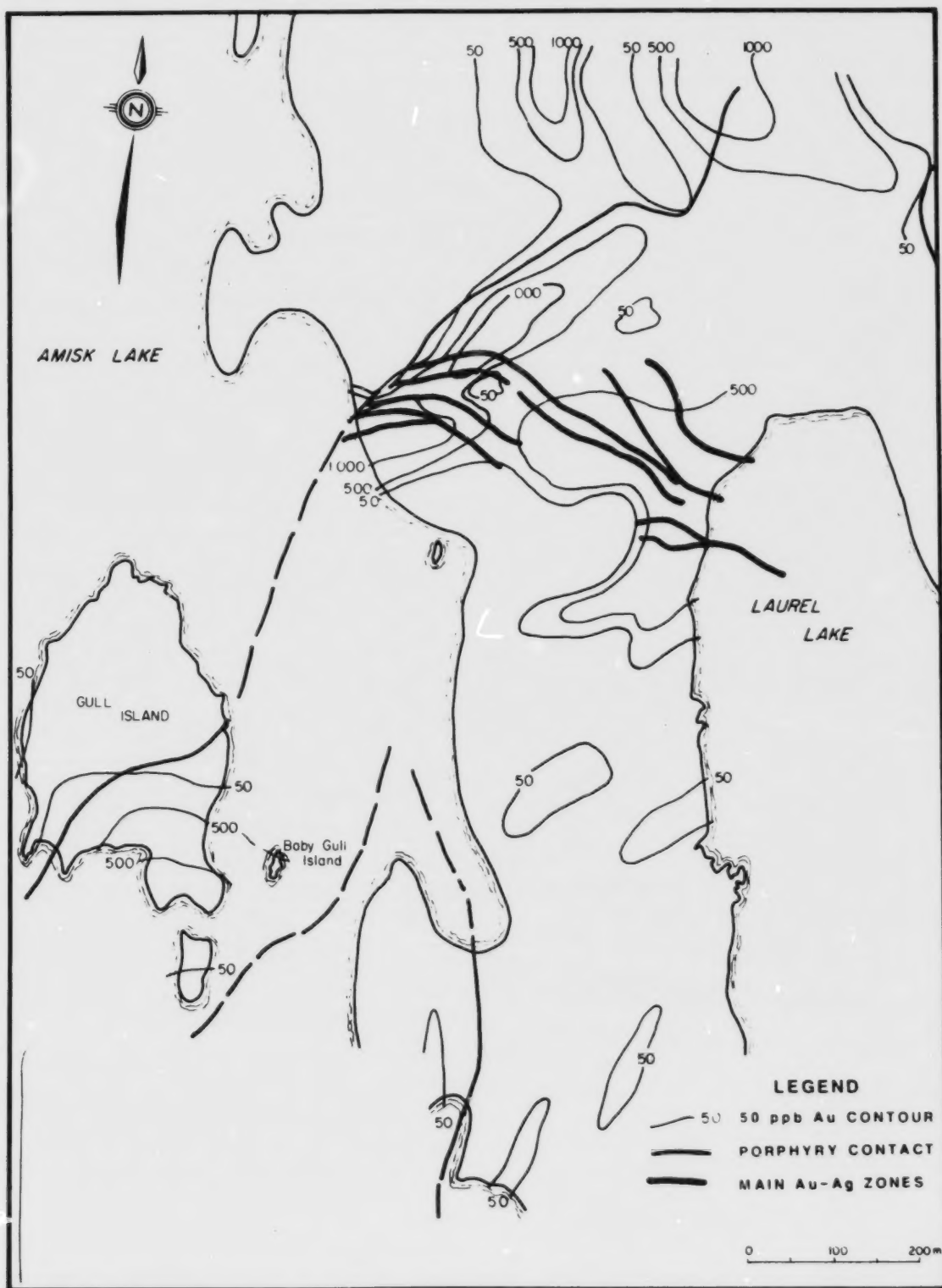


Figure 5. Contoured lithogeochemical gold values in the Laurel Lake porphyry and some parts of the overlying intermediate to mafic tuffs.

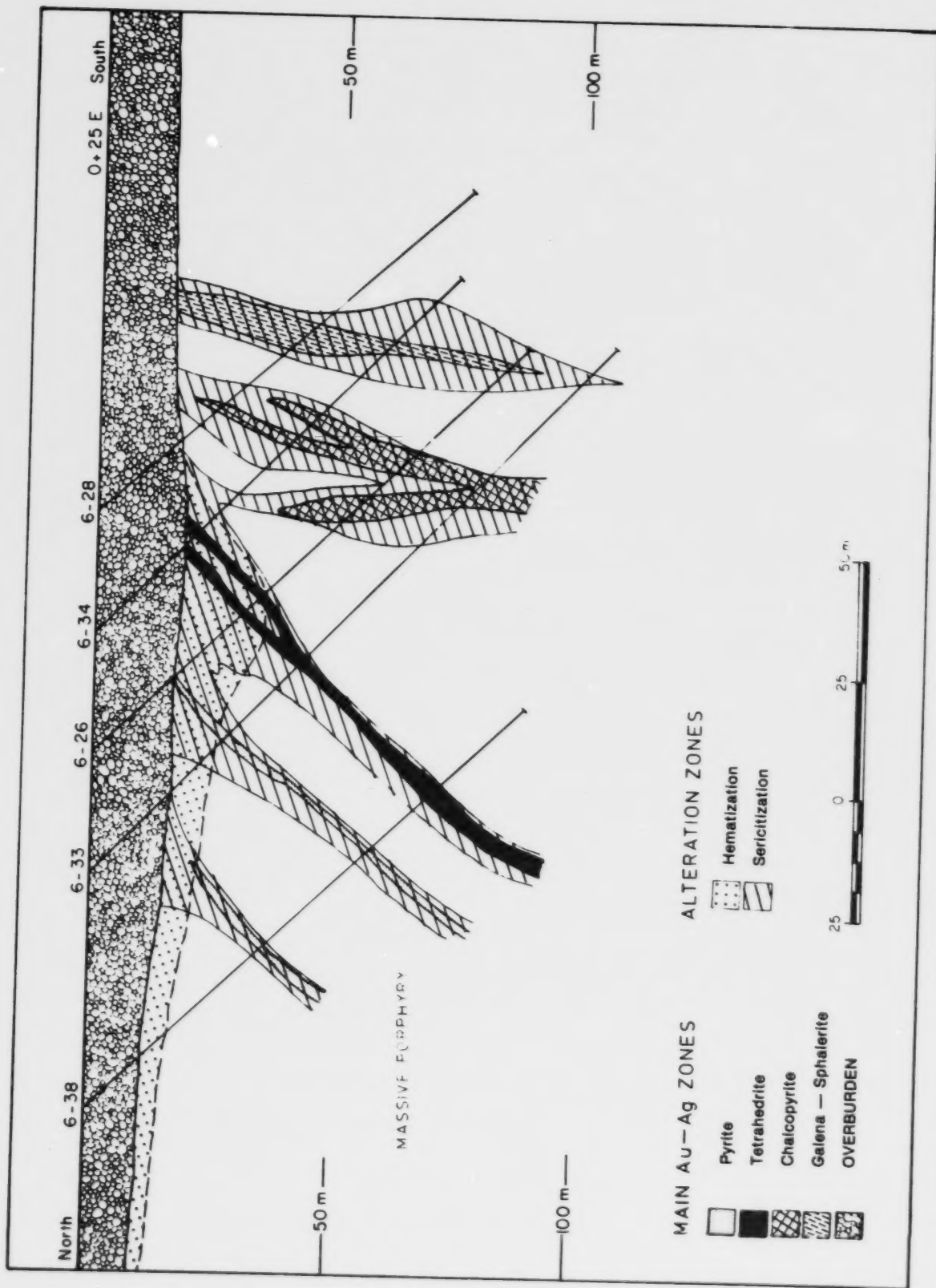


Figure 6. Generalized cross-section of the Laurel Lake Zone.

the massive portion of the porphyry stock, the ratio of silver to gold values is approximately 10:1. As the system passes upwards into the overlying fragmental rocks, the silver to gold ratio rapidly decreases until the gold content is equal to or greater than that of silver just below the basic tuff contact.

From limited polished thin-section work, most of the gold appears to occur as fine specks of free gold in fractures in, and along intergranular boundaries between, sulphide grains. Only three sightings of visible gold have been recorded in drill core. However, all polished sections from high-grade sulphide intersections contain free gold, most commonly in direct association with enargite and chalcopyrite.

Analysis of copper, lead, and zinc in sludge samples from a selection of drill holes situated in the massive portion of the stock shows a direct correlation exists between copper and gold contents in all the subzones. Zinc contents display partial correlation with gold, and lead, little or no such correlation.

CONCLUSIONS

The distribution and types of alteration and mineralization associated with the Laurel Lake - Gull Island porphyry body indicate a synvolcanic epithermal depositional model for the precious-metal mineralization.

The geological environment, mineralization, and alteration patterns at Laurel Lake are similar to those found in recent porphyry bodies in the western United States.

The distributions of silver to gold ratios, of base metals, and of alteration generally conform to Buchannan's (1981) epithermal model, both in scale and in relation to the inferred geological environment.

REFERENCES

Bruce, E.L., 1918, Amisk — Athapapuskow Lake district: Geological Survey of Canada Memoir 105, 91 p.

Buchannan, L.J., 1981, Precious metal deposits associated with volcanic environments in the southwest United States; relations of tectonics to ore deposits in the Southern Cordillera: Arizona Geological Society Digest, v. 14, p. 237-262.

Byers, A.R., and C.D.A. Dahlstrom, 1954, Geology and mineral deposits of the Amisk-Wildnest Lakes area, Saskatchewan: Saskatchewan Department of Mineral Resources Report 14, 177 p.

Fox, J.S., 1976, Some comments on the volcanic stratigraphy and economic potential of the west Amisk Lake area, Saskatchewan: Saskatchewan Research Council Circular 9.

Macdonald, R., 1981, Compilation bedrock geology: Pelican Narrows and Amisk Lake areas (NTS 63M, 63L, part of 63N and 63K); at 1:250,000 scale, in J.E. Christopher and R. Macdonald, eds., Summary of Investigations 1981, Saskatchewan Geological Survey: Saskatchewan Energy and Mines Miscellaneous Report 81-4.

Van Wagoner, N., and S. van Wagoner, 1981, Shallow water volcanism and sedimentation in a portion of the Flin Flon — Snow Lake greenstone belt: in Centre for Precambrian Studies 1981 Annual Report, University of Manitoba, Winnipeg, p. 71-88.

Walker, D., and B.R. Watters, 1982, Geochemistry of metavolcanic rocks, Amisk Lake west area, in R. Macdonald, T.I.I. Sibbald, D.F. Paterson, P. Gulioy and J.V. Buller, eds., Summary of Investigations 1982, Saskatchewan Geological Survey: Saskatchewan Energy and Mines Miscellaneous Report 82-4, p. 24-30.

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THE STAR LAKE PLUTON AND ITS GOLD MINERALIZATION — AN OVERVIEW

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ABSTRACT

The Star Lake Pluton is a calc-alkaline pre-tectonic composite intrusion emplaced into a Lower Proterozoic oceanic island arc volcanosedimentary sequence in northern Saskatchewan. Upper greenschist to lower amphibolite grade metamorphism related to Hudsonian thermotectonism has affected the intrusion and its supracrustal envelope. The pluton displays a marked concentric zonation of rock types ranging from a gabbro-diorite marginal phase, through a monzonite-granodiorite-quartz monzonite transitional phase, to a granite central phase. Geochemical variation diagrams display almost linear inter-element trends which exhibit increasing SiO₂, K₂O, Na₂O and decreasing FeO and MgO contents from the marginal to the central zones of the intrusion. A progressive decrease in total REE contents from the margin to the centre of the body is attributed primarily to the involvement of amphibole in the evolution of the magmas. The Star Lake Pluton is interpreted as an I-type felsic intrusion generated by partial melting of meta-igneous rocks in the roots of an island arc.

The pluton is intruded by northeasterly trending dyke swarms ranging in composition from ultramafic and mafic through intermediate to felsic. Northeast-trending ductile shear zones which deform the pluton are commonly centred along these dykes. The dykes may have acted as zones of weakness along which the shear strain was most easily accommodated. Gold-bearing pyritic and pyrrhotitic quartz veins within the shear zones are prevalent throughout the intrusion, and are considered to have been emplaced contemporaneously with shearing as a single progressive 'crack and seal' event.

One shear-controlled vein containing 210,000 tonnes at 17.0 g/t Au is presently being exploited at the Star Lake Mine. The Rod Zone, which has drill-indicated reserves of 810,000 tonnes at 20.9 g/t Au, is presently awaiting an underground exploration phase.

THE STAR LAKE PLUTON AND ITS GOLD MINERALIZATION — AN OVERVIEW

INTRODUCTION

The Star Lake Pluton is located in the Central Metavolcanic Belt of the La Ronge Domain which forms part of the Lower Proterozoic Trans-Hudson Orogen. The Central Metavolcanic Belt is narrow, trends northeastwards, is 10 to 20 km in width, and extends for about 150 km from La Ronge to Reindeer Lake. It comprises metavolcanic and minor intercalated metasedimentary rocks which are intruded by felsic to mafic plutons. A molasse-like assemblage of feldspathic meta-arenites and metaconglomerates of the McLennan Group structurally underlies the Central Metavolcanic Belt to the southeast. To the northwest, a monotonous sequence of metagreywackes, termed the Crew Lake Belt, structurally and stratigraphically overlies the metavolcanic belt. The Central Metavolcanic Belt is variably deformed and metamorphosed

to upper greenschist to lower amphibolite facies grade. Primary volcanic and sedimentary features are commonly well preserved. Shear zones or belts of high strain are developed along the southeastern and northwestern flanks of the Belt, and are marked by an increase in metamorphic grade to middle and upper amphibolite facies. Zircon (U-Pb) dating indicates an age of emplacement of about 1870 Ma for the volcanic rocks and 1850 Ma for the plutonic components in the Belt.

PETROLOGY

The Star Lake Pluton is a compositionally zoned composite intrusion which has been emplaced within an intermediate to mafic sequence of dominantly subaqueous volcanoclastic and lava-flow units. In plan, the intrusion is an 18 km² pear-shaped body, elongated along a north-northeast axis (Fig. 1). The pluton displays a marked concentric zonation ranging from a gabbro-diorite marginal phase, through a monzonite-

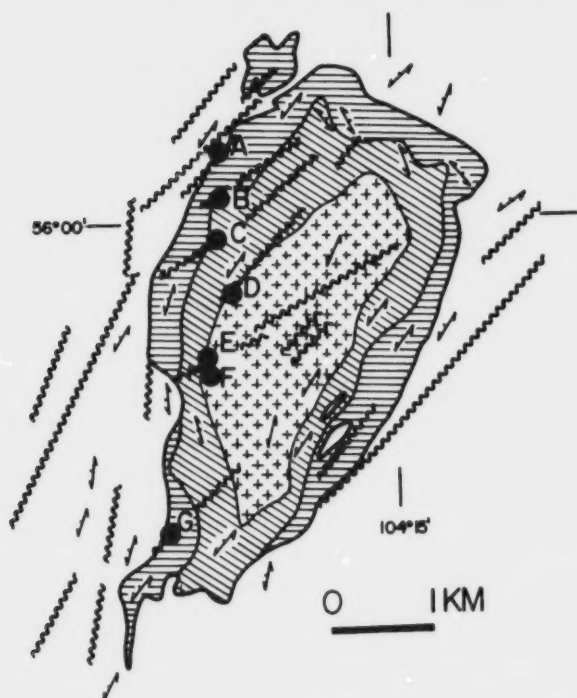


Figure 1. Simplified geological map of the Star Lake Pluton. Gabbro-diorite marginal phase (horizontal lines), monzonite-granodiorite-quartz monzonite 'transitional' phase (diagonal lines), and granite central phase (crosses). Gold occurrences: Jolu occurrence (A), Rod Zone (B), Pie/Rush occurrence (C), Blindman Zone (D), Star Lake Mine/21 Zone (E), Kahn 18 occurrence (F), and Tamar occurrence (G). Foliation symbols refer to the S_1 fabric.

granodiorite-quartz monzonite 'transitional' phase to a granite central phase. Modal estimates clearly indicate an increase in quartz and potassium feldspar toward the centre of the body, and SiO_2 contents range from a low of 47 per cent in the marginal phase to a maximum of 74 per cent in the central phase. Transitions between the zones are generally gradual or diffuse, although crosscutting intrusive relationships are also present. The marginal gabbro-diorite is clearly the most heterogeneous phase, both compositionally and texturally. Hornblende is the principal mafic mineral in the marginal phase, and occasionally occurs mantling cores of relict pyroxene. Biotite is the principal mafic mineral in the transitional and central zones. Plagioclase phenocrysts in the more basic to intermediate rocks are commonly poikilitic and display oscillatory zoning.

The pluton hosts an array of xenolithic material including volcanic fragments in the marginal zone and subrounded cognate dioritic xenoliths in the more felsic phases. Northeasterly trending dyke swarms, ranging in composition from ultramafic and mafic through intermediate to felsic, transect the pluton. The dykes vary in width from a few centimetres to a few metres and extend for as much as several hundred metres along strike. In general, an evolutionary trend from early ultramafic and mafic dykes to later intermediate and felsic varieties is apparent.

Geochemical data indicate a calc-alkaline character for the intrusion. Rocks from the marginal phase are compositionally the most variable, and those from the 'transitional' and central

phases of the body display a remarkably tight linear trend on an AFM plot (Fig. 2). Chondrite-normalized REE profiles for the three phases of the intrusion are similar in shape to each other, and total REE contents decrease progressively from the marginal zone to the central zone (Fig. 3). When plotted on a Rb against $(Y + Nb)$ discrimination diagram (Fig. 4), a volcanic-arc granite character is indicated, and is consistent with the tectonic setting inferred from the geochemistry and lithology of the volcanic sequence into which the Star Lake Pluton was emplaced.

Geochemical, petrographic and field data suggest that initial development involved localized melting of amphibolitic rocks in the roots of the La Ronge volcanic arc to produce gabbro-dioritic magmas. Magma compositions at this stage were probably variable due to differences in their source rocks. Following initial injections of a heterogeneous mafic magma into the site of the Star Lake Pluton, a larger reservoir of more homogeneous calc-alkaline magma developed as partial melting became more extensive. Fractionation of this more homogeneous magma, involving primarily amphibole, took place during intermittent, or perhaps continuous, 'streaming' of melt into the site of the Star Lake Pluton. Some in situ fractionation may have occurred in the central phase of the body.

DEFORMATION

All rocks comprising the Star Lake Pluton possess a weak to moderate metamorphic fabric (S_1) which is generally conformable in the marginal zone to the contact of the intrusion with supracrustal rocks. In the 'transitional' and central zones, S_1 has a mainly north-northeasterly trend and dips steeply to the northwest. The general orientation of S_1 in the pluton is consistent with S_0 (bedding) and S_1 foliations in the surrounding metavolcanic sequence.

Northeast-trending ductile shear zones cut the pluton. They range in width from only a few centimetres to 30 metres, and are traceable for up to 1000 metres along strike. Typically,

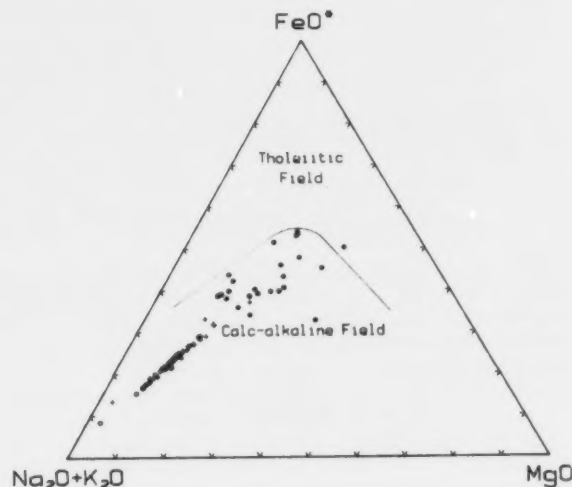


Figure 2. AFM plot for rocks from the Star Lake Pluton. Full circles, marginal zone; crosses, 'transitional' zone; open circles, central zone. Field boundaries from Irvine and Barager (1964).

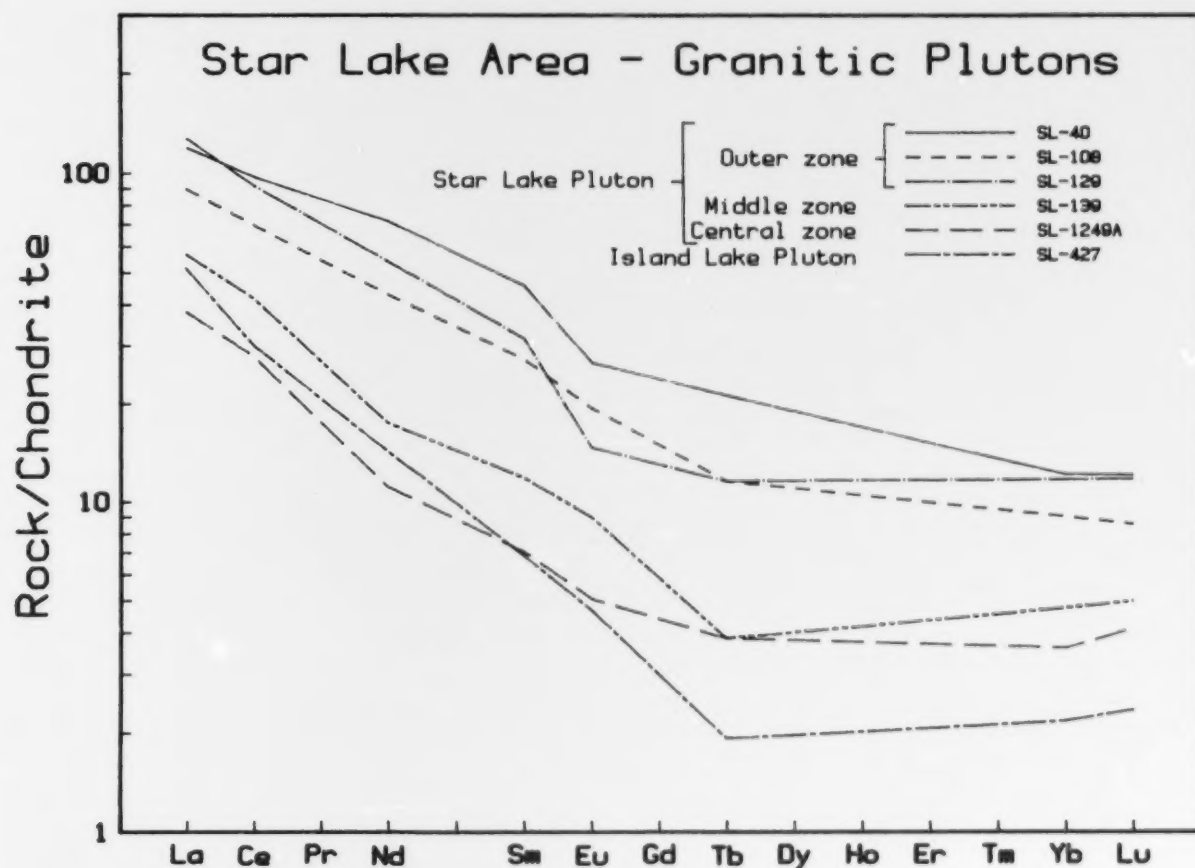


Figure 3. Chondrite-normalized REE distribution patterns for the Star Lake Pluton and, for comparison, the Island Lake Pluton.

they are made up of minor, anastomosing shear zones which give a 'pinch and swell' character to the major structures. The shears generally dip steeply to the northwest, although local reversals in dip suggest that the structures 'roll-over' in places. These structures postdate the weaker, more pervasive metamorphic foliation. The dykes, which are commonly sheared, may have acted as zones of weakness along which the shear strain was most easily accommodated. Sheared rocks exhibit an intensification of penetrative foliation ranging from well foliated through protomylonitic to, locally, mylonitic.

GOLD MINERALIZATION

Gold mineralization in the Star Lake Pluton occurs in structurally controlled quartz veins emplaced into shear zones. The gold-bearing quartz veins form long, roughly lozenge-shaped bodies of variable size. En echelon lenses of quartz up to several metres in thickness are commonly developed in individual shear systems. The quartz lenses preferentially occupy the concave side of subtle flexures in these shears and so are commonly bounded by sheared wallrock on one side and massive wallrock on the other. Elongated wallrock fragments of either dyke or granitoid material are generally incorporated into the quartz bodies. The central parts of the quartz lenses generally possess a blocky, breccia-like texture, whereas the ends of the lenses comprise multiple sets of

narrow, sheared quartz veinlets. The emplacement of the quartz lenses is considered to have been contemporaneous with shearing and to have occurred during a single progressive event whereby, as incremental movement proceeded along any particular shear structure, the ends of the quartz veins became incorporated into the shearing. Subsequent failure by 'cracking' of the main part of the vein system was accompanied by emplacement of younger quartz veins. Commonly, early vein-quartz and incorporated wallrock fragments were folded or brecciated and subsequently invaded by younger quartz veins. This internal 'crack and seal' structure is particularly well illustrated in underground exposures at the Star Lake Mine.

Gold is typically accompanied by iron sulphides in the quartz veins. At the Jolu and Rod occurrences, in the northern part of the intrusion, pyrrhotite and pyrite are the principal sulphides. Molybdenite is also present in appreciable amounts in the Rod occurrence. Auriferous quartz veins in the marginal gabbro-diorite phase also contain tourmaline and chlorite. In the 21 Zone, and in the Blindman and Kahn 18 occurrences, the veins are hosted by the more felsic rocks of the intrusion, and gold is principally associated with coarse, generally euhedral, pyrite. Biotite is the main mafic silicate gangue mineral present in the veins. Extensive hydrothermal alteration is, for the most part, absent around the quartz veins, although

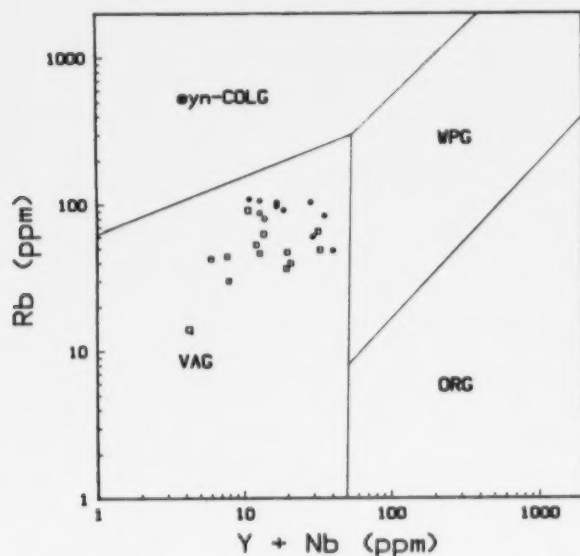


Figure 4. Rb against (Y + Nb) discriminant plot for 'granitic' rocks (SiO₂ greater than 56 per cent) from the Star Lake Pluton (closed circles) and, for comparison, the Island Lake Pluton (open circles) and plutons from the Waddy Lake area (squares). Field boundaries are from Pearce et al (1984).

tourmaline pods locally increase in size and abundance towards some shear structures in the marginal phase of the pluton. A weakly to strongly developed bleaching of the

country rock is also apparent around the larger tourmaline pods. Late, brittle fractures containing hematite and clay minerals are associated with many of the vein systems.

To date, seven areas of significant gold mineralization have been identified in the Star Lake Pluton. Three of these occurrences (Jolu Vein, Rod Zone, and 2l Zone) have a cumulative reserve of about 1.06 million tonnes at an average grade of 18.0 grams per tonne Au. Production from the 2l Zone at the Star Lake Mine (210,000 tonnes at 17.0 g/t Au) started in early 1987. The Rod Zone (810,000 tonnes at 20.9 g/t Au), which was discovered in 1984, is now being examined underground by Royex Gold Mining Corporation; a detailed feasibility report is scheduled for submission on September 1, 1987. Over a relatively short time span, the Star Lake Pluton has become a major focus of attention in the La Ronge Gold Belt play in northern Saskatchewan.

REFERENCES

- Irvine, T.N., and W.R. Barager, 1971, A guide to the chemical classification of the common volcanic rocks: *Canadian Journal of Earth Sciences*, v. 8, p. 523-548.
- Pearce, J.A., N.B.W. Harris, and A.G. Tindle, 1984, Trace element discrimination diagrams for the tectonic interpretation of granitic rocks: *Journal of Petrology*, v. 25, p. 956-983.

THE GEOLOGY AND MINERALIZATION OF THE MALLARD LAKE GOLD PROPERTY, NORTHERN SASKATCHEWAN

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ABSTRACT

Gold was first discovered on the Mallard Lake property in 1944. The property's economic potential began to be fully revealed in 1984, when Mahogany Minerals Resources Inc. made a second significant gold discovery, the Rod structure, thus opening Mallard Lake to major exploration efforts.

To date, gold has been found within three discrete structures, the Mallard, the Rod Main, and the Perch. Although the Rod Main contains the vast majority of the known mineralization, the others require further evaluation.

INTRODUCTION

The Mallard Lake property is located in the La Ronge Mining District of Saskatchewan. It lies approximately 10 kilometres west of Highway 102 at 104° 16' west longitude and 56° 02' north latitude, some 120 kilometres north-northeast of the town of La Ronge (Fig. 1).

Gold was discovered in the Mallard Zone in 1944 by J.E. Coffyne and L. Garskie who were prospecting the area on behalf of Cominco.

Since then, various operators, have kept the property in good standing with respect to assessment requirements. Oklend Gold Mines Ltd. optioned the property from Cominco in 1962 and, after obtaining disappointing results from a small exploration program, dropped interest. Cominco resumed performing small exploration programs until 1972, when the property was optioned to M.A. Roed who, after a limited drilling program, transferred the property to Decade Development Ltd. This company put the Jolu deposit into production. Intermittently over the period 1973-75, it and other operators milled approximately 5,000 tons of ore from which about 558 ounces of gold and 49 ounces of silver were won (Coombe 1984).

Mahogany Minerals Resources Inc. acquired the property in 1982. In 1984, Goldsil Resources Ltd. acquired control of Mahogany and initiated the exploration program which has continued through to the present and which has entailed ground magnetic, VLF, and soil geochemical surveys as well as detailed prospecting. The last of these methods led to the discovery of the Rod Zone in 1984.

REGIONAL GEOLOGY

The area is located in the centre of the La Ronge Domain (Fig. 2), which has been subdivided into a central portion composed predominantly of metavolcanic rocks with minor intercalated volcanogenic metasediments; a western portion composed

predominantly of turbiditic metasediments; and an eastern portion composed mainly of psammitic metasediments. The chronological relationships of the rocks in the La Ronge Domain are controversial. Some workers in the area consider that the units young to the west, others that the rocks represent a former island arc and that the flanking (meta)sediments were penecontemporaneously deposited.

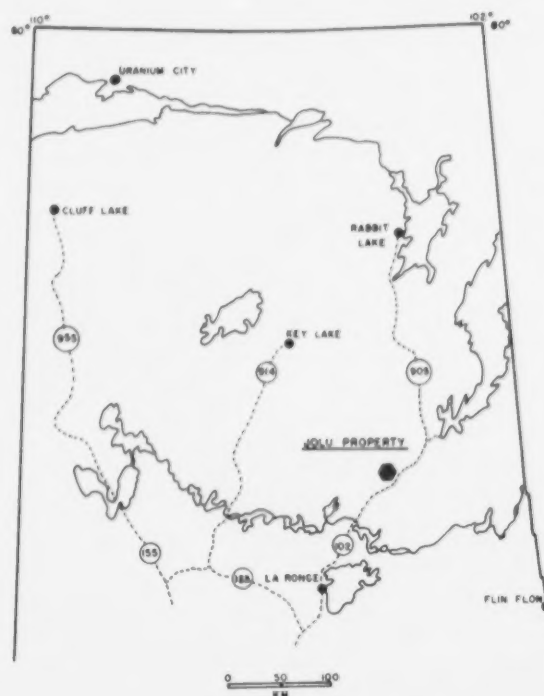


Figure 1. Location map.



Figure 2. General geology and major subdivisions of the Churchill Province in northern Saskatchewan (from Coombe, 1984, after Lewry and Sibbald, 1980).

Rocks of intermediate to felsic composition have intruded the supracrustal sequence, and make up almost 40 per cent of the La Ronge Domain. Generally, leucodiorites to monzodiorites constitute the early intrusive phases, which are commonly followed by phases of granitic to monzonitic composition.

Figure 3 illustrates the geology in the broad vicinity of the Mallard Lake property.

LOCAL GEOLOGY

STRUCTURE

The dominant, regionally developed set of shear zones traverses the property at about 060° with minor sets striking at 045° and 095°. An early, weakly developed regional tectonic foliation, S_1 , strikes approximately 050° to 060° and dips 70° to 75° to the northwest. Thus, the main structural elements are roughly parallel to the structural fabric of the La Ronge Domain itself.

To date, gold mineralization has been encountered within three of the 060°-trending shears: the Mallard, the Perch and — most importantly — the Rod. Each of these structures is subvertical. The Rod is the largest in width, length, sulphide content, quartz development, and accumulated gold.

SUPRACRUSTAL ROCKS

The Mallard Lake property is underlain by a complex assemblage of intercalated, weakly metamorphosed sedimentary and volcanic rocks. The sedimentary rocks, which strike 025° to 040° and dip westwards at 60° to 70°, range from volcanogenic argillites to water-lain tuffs and agglomerates. Rapid vertical and lateral lithologic changes make correlation extremely difficult, if not impossible.

The volcanic rocks, for the most part range from andesites to felsitic dacites; mafic volcanics are rare.

INTRUSIVE ROCKS

A diorite-granodiorite-monzonite pluton emplaced into the supracrustal rocks occupies the eastern half and the northern edge of the Mallard Lake property. Evidence from drilling indicates that the pluton is composite, consisting of several distinct intrusive events, one or more of which may have featured in situ differentiation.

In the east, the rocks near the margin of the pluton range from diorite to quartz-diorite, and exhibit persistent deuteric features; towards the core of the pluton, the rocks range from granodiorite to monzodiorite. A sharp, clear, intrusive contact exists between the outer dioritic complex and the inner granodioritic core. Near this contact, the granodiorite exhibits minor crystal-size reduction and an hypidiomorphic granular texture; however, in a marginal zone some 10 to 20 metres wide, it grades into diorite (not the same rock type as that in the outer dioritic complex), apparently a result of magmatic differentiation.

The Rod structure cuts the pluton at approximately 060°. It offsets the diorite-granodiorite contact by approximately 200 metres, displacing the northwestern flank northeastwards. The majority of the economic-grade gold found to date occurs within this offset (Fig. 4).

The northern edge of the property is underlain by intrusive rock that is compositionally much more basic than in the east.

This more basic rock may have been derived from a discrete melt, but may alternatively have been a very early intrusive stage of the eastern pluton.

The two main plutonic rock types have drastically different magnetic signatures. Typically, the granodiorite offers a broad, low-intensity flat signature whereas the diorite exhibits sharp, generally high-intensity magnetic relief.

The pluton has been intruded by narrow dykes ranging in width from a few centimetres to two metres. The dykes mostly strike northeastwards (040° to 050°) and dip subvertically. Compositionally, they range from mafic through intermediate to acid.

Trending approximately 10° to 15° north of the Rod Main structure (i.e. striking at 045° to 050°), a swarm of mafic dykes cuts the granodiorite and, upon entering the mylonite zone, has been incorporated into the structure, forming (in places) 100 per cent of the zone. These dykes have been subdivided into lamprophyric and doleritic types, both of which are believed to have been contemporaneously emplaced. They cut an older set of dark grey, fine- to medium-grained dykes of intermediate composition (diorite and quartz diorite). All these types of dykes have been intersected in both the hanging walls and footwalls of the Rod structure as well as in the structure itself.

Acid dykes (aprites and quartz-feldspar porphyries), although parallel to the mafic dykes, are of unknown relative age. They have not yet been found within the mylonite, but evidence is currently lacking to show whether this is because they do not occur in appropriate places or because they were injected after mylonitization took place.

MINERALIZATION — MALLARD ZONE

Gold mineralization is structurally controlled in the Mallard Zone by a shear system (striking 057° and dipping 80° to 85° to the southeast) located at the contact between the diorite-granodiorite pluton to the southeast and supracrustal rocks to the northwest.

The mineralized shear system cuts sedimentary rocks, mostly greywackes, at its southwestern end for a length of approximately 150 metres. The northeastern portion of the structure either forms the contact between the intrusive and sedimentary rocks, or cuts hornfels-facies quartz-biotite-garnet schists formed by contact metamorphism of the country rock.

Mineralization has been traced intermittently along this shear system for approximately 150 metres to depths of up to about 65 metres. It is found within, or adjacent to, a quartz-vein system which exhibits late-stage brittle fractures infilled by chlorite, tourmaline, calcite, and amphibole (most commonly actinolite). The best gold accumulations are closely associated with elevated sulphide concentrations of about 10 to 15 per cent, where pyrrhotite is about seven times as abundant as other sulphides (pyrite with subordinate chalcopyrite, molybdenite and, in places, marcasite).

The quartz veins attain widths of 0.3 to 5.8 metres and plunge gently to the west.

MINERALIZATION — ROD ZONE

The Rod Zone occurs in mylonite striking approximately 060° across the Star Lake Pluton. It varies in width from 3 to more

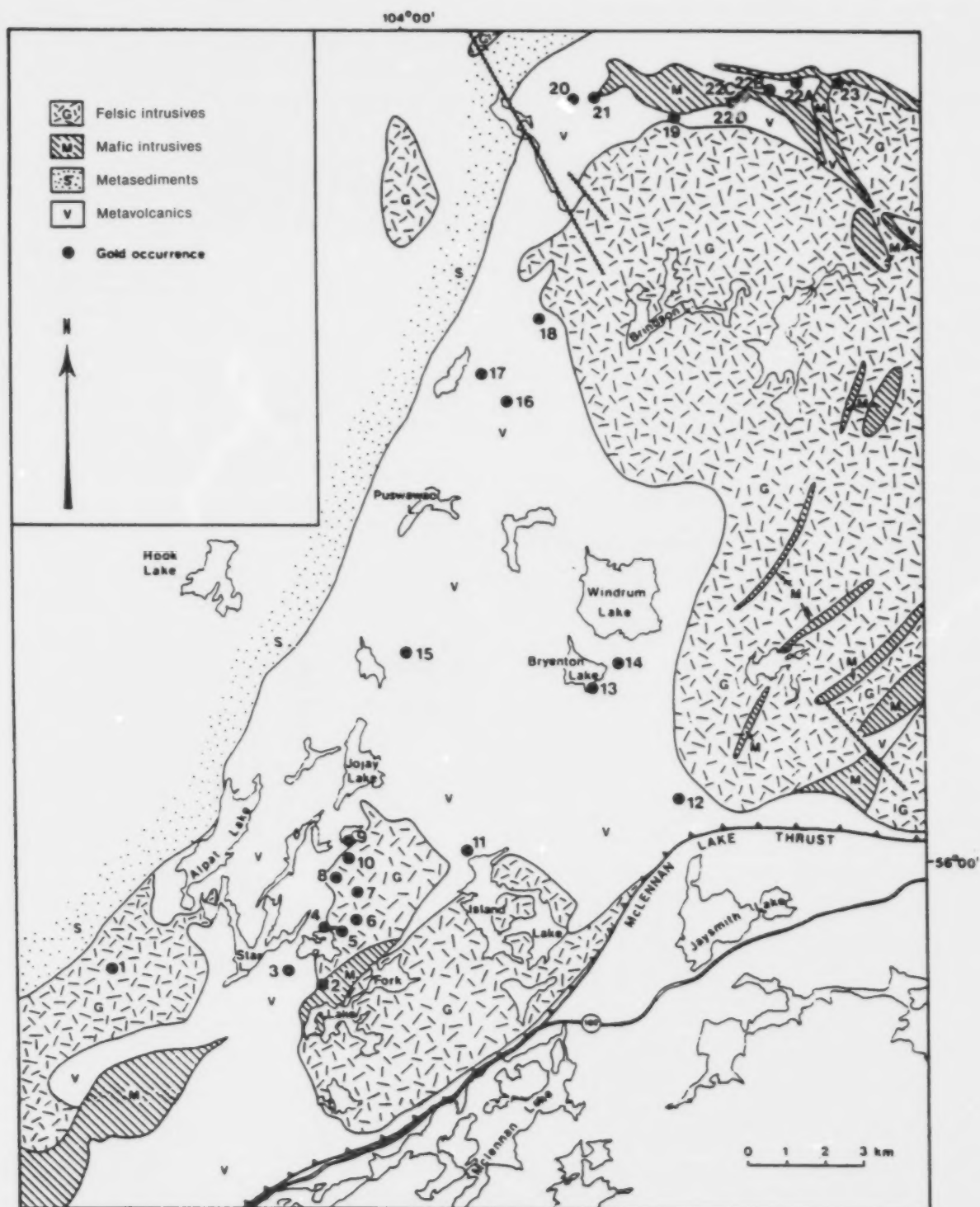


Figure 3. Geology and gold occurrences in the Star-Windrum Lakes area (from Coombe, 1984, after Budding, 1955; Gracie, 1967; Miller, 1949; Morris, 1961).
 Key: 1, Como Lake; 2, Tamar; 3, Star Vein 1; 4, Garskie and Coffyne Veins; 5, Kahn 18 Vein and Starrex 21 Zone; 6, Kahn 28 Vein; 7, Blindman's Lake; 8, Pie; 9, Jolu (Devade Mine); 10, Rod Zone; 11, Drew; 12, Keta; 13, Allen Veins 1, 3 and 4; 14, Allen Vein 2; 15, Jojay; 16, Hayes Lake; 17, Exit (Ahole) Lake; 18, Exit Lake, ENE; 19, Kaslo; 20, Centre Lake, West; 21, Centre Lake; 22, Tower Lake, West; 23, Tower Lake, East.

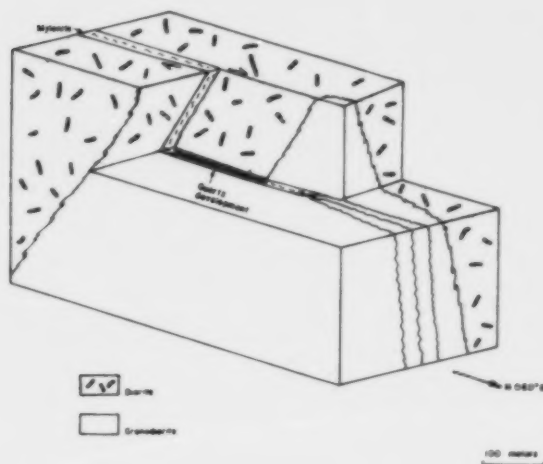


Figure 4. Schematic representation of the Rod structure.

than 20 metres — the character of the structure reflecting the plasticity of the host rock through which it passes. Horizontal displacement in the immediate vicinity of mineralization is about 200 metres, with the northwestern block displaced northeastwards relative to the southeastern block. Vertical throws have not yet been ascertained.

Along strike, the structure changes character (Fig. 4).

In its southwesternmost portion, where diorite forms both footwall and hanging wall, the mylonite zone is broad and dips very steeply to the south. Quartz is developed locally as ribbons parallel to the mylonitic foliation. Sulphides (three to five per cent) are finely disseminated. The mylonite feathers out into the host rock.

Where the mylonite offsets the diorite-granodiorite contact, the structure narrows by approximately 20 per cent. It dips 85° to 83° to the southeast and maintains very sharp, consistent boundaries.

Northeast of the footwall diorite-granodiorite contact where both the hanging wall and footwall are composed of granodiorite, the mylonite zone splits into three branches, each of which — in places — anastomoses both vertically and horizontally. Here, the zone is vertical or dips very steeply to the northwest.

The structural styles are believed to have been influenced by the plasticity of the rock types affected. The relatively soft diorite exhibits a greater number of plastic deformation features than the granodiorite.

These tectonic characteristics are extremely important as all gold mineralization of the Rod Zone was structurally controlled. Since changes in structure ultimately influenced deposition from ore-bearing fluids, they must be understood in order to define the pattern of mineralization in terms of location, geometry, and grade.

Gold mineralization occurs in four discrete configurations in the Rod Zone. These are:

1) tensile veinlets within the granodiorite,

- 2) veins hosted by the Rod Zone proper,
- 3) quartz replacement of mafic dykes and
- 4) a stockwork.

All four configurations produce high assays and are sulphide-bearing.

1. TENSILE VEINLETS WITHIN THE GRANODIORITE

Tensile quartz veins containing economically significant amounts of gold have been found in the hanging wall of the Rod structure, most abundantly at its northeastern end where its dip has rolled over to the northwest. They have also been found in other locations, but lack economic significance. Their contacts are, in places, extremely irregular; elsewhere, they are sharp enough to be traced from drill hole to drill hole. Gold, where present, is generally sulphide associated and coarse grained (visible). Sulphide, usually very coarse pyrrhotite with minor pyrite and accessory chalcopyrite and molybdenite, forms up to 50 per cent of the host rock. Where pyrite is the dominant sulphide, gold may be very fine grained and, therefore, difficult to identify.

2. VEINS HOSTED BY THE ROD ZONE PROPER

These veins contain the majority of the gold in the Rod Zone and are therefore considered to be the most important type of mineralization. They are hosted by mylonite which is subvertical or dips approximately 85° to the southeast, and which averages 5 to 7 metres in width but, in places, reaches widths of 12 metres. The thickest quartz accumulations are located where a lithological change occurs across the Rod structure — for example, where granodiorite forms the hanging wall, diorite the footwall (Figs. 4 and 5). Another lithological distinction peculiar to these highest gold-grade regions in the Rod structure is the consistent presence of mylonitized mafic dykes.

Gold is visible in all samples which have proven assays, and is directly associated with sulphides. The best assays have been obtained from samples containing about ten per cent pyrrhotite and pyrite in a ratio of seven to one, along with a trace to 0.5 per cent chalcopyrite and trace amounts of molybdenite. Biotite-actinolite banding through the quartz also appears to be a closely associated phenomenon, and gold has been seen within these bands as fine dusting or at band-edges as coarse flecks. Gold has also been identified in blue-grey quartz, and in hairline fractures through quartz of various colours.

The richest mineralization occurs at the contact between diorite and granodiorite in the footwall, and has been consistently traced for almost 400 metres along this feature.

3. QUARTZ REPLACEMENT OF MAFIC DYKES

In the hanging wall of the Rod structure, quartz veins which are parallel or subparallel to the structure appear to have replaced mylonitized lamprophyre dykes. They range from 0.5 to 2.0 metres in width and are, again, sulphide-bearing. As in the main-zone veins, the best gold assays are obtained from pyrrhotite-dominated samples with accessory pyrite, chalcopyrite and molybdenite. Locally, the replacement veins take on a pegmatitic appearance. Actinolite is always present along with calcite and, in places, tourmaline. This replacement mineralization is sometimes referred to as the "Rod South Type".

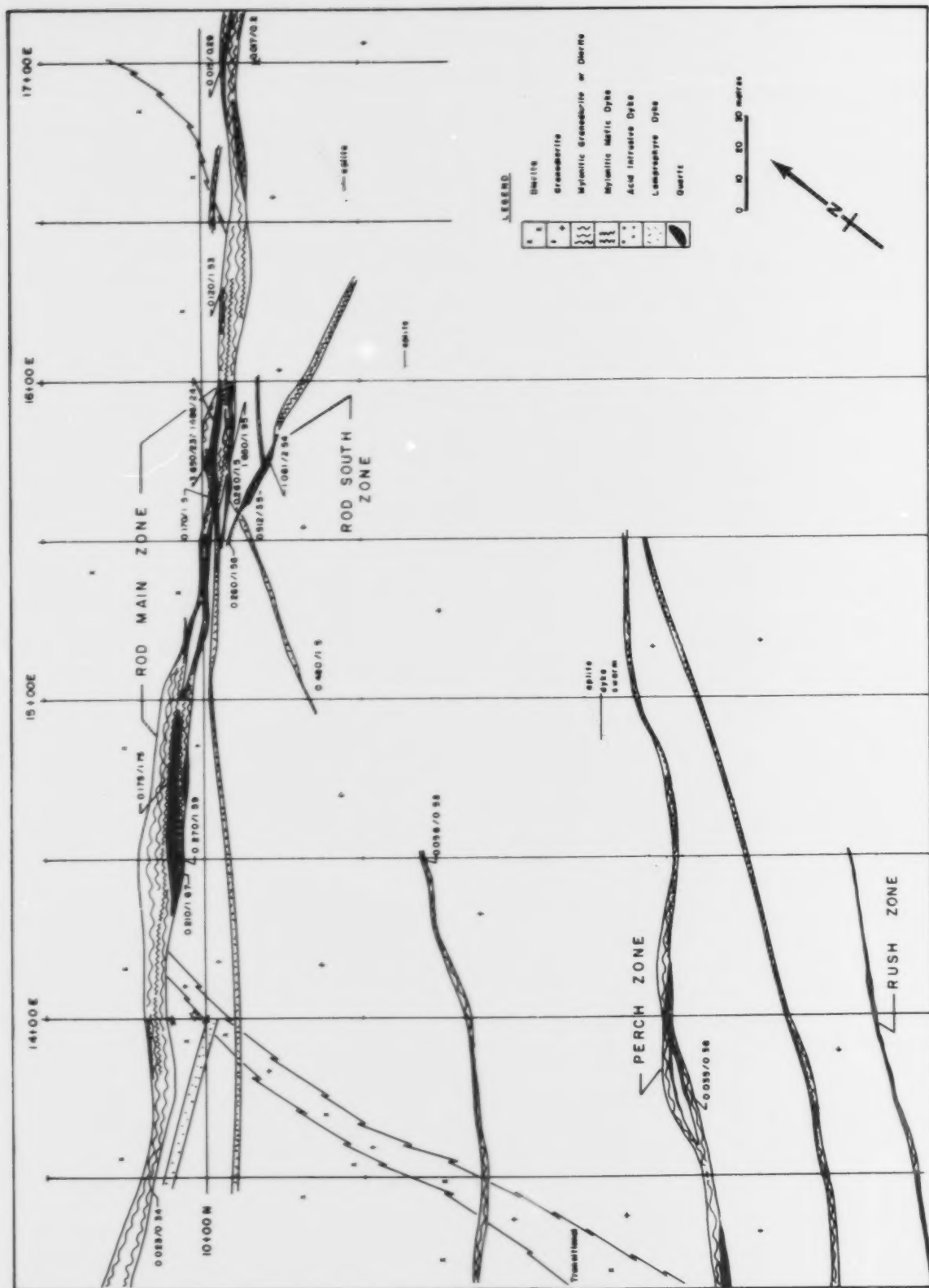


Figure 5. Plan view of the Rod Zone (1925 m above sea level).

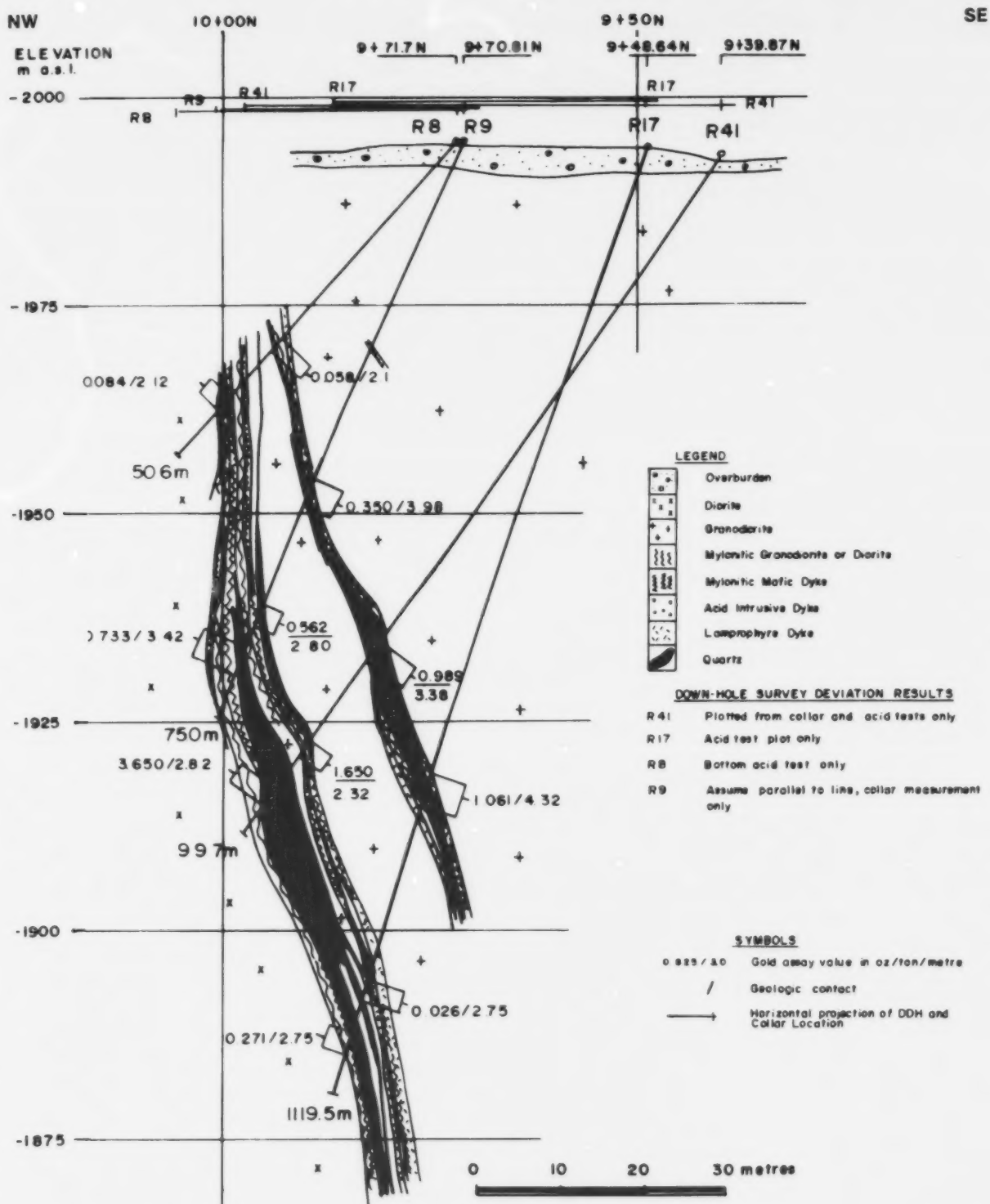


Figure 6. Cross-section of the Rod Zone along 15 + 75E, showing drill holes R8, 9, 17 and 41.

4. A STOCKWORK

A stockwork has been found in the deepest explored portions of the Rod Zone in an area where the main mylonite bifurcates, enveloping quartz-cemented, brecciated granodiorite (Fig. 6). The silicification which led to quartz-cementation was accompanied by the introduction of sulphides, dominantly pyrite. Gold mineralization in this environment is much finer grained than in those areas previously discussed, and has been visually identified very rarely, mostly in association with actinolite and calcite.

REFERENCES AND SELECTED BIBLIOGRAPHY

- Budding, A.J., 1955, The geology of the Settee Lake area (east half): Saskatchewan Department of Mineral Resources Report 17, 19p.
- Burrill, G.H.R., 1985, 1986, Internal Reports: Burrill Exploration Ltd.
- Coombe, W., 1984, Gold in Saskatchewan: Saskatchewan Energy and Mines Open File Report 84-1.
- Gracie, A.J., 1967, The geology of the Maribelli Lake area (west half), Saskatchewan: Saskatchewan Department of Mineral Resources Report 113, 27 p.
- Hubregtse, J.J., 1986, Internal Report: Mahogany Minerals Resources Inc.
- Lewry, J.F., and T.I.I. Sibbald, 1980, Thermotectonic evolution of the Churchill Province in northern Saskatchewan: Tectonophysics, v. 68, p. 45-82.
- Miller, M.L., 1949, The geology of the Windrum Lake area, Saskatchewan: Saskatchewan Department of Mineral Resources Report 3, 24 p.
- Morris, A., 1961, The geology of the Settee Lake area (west half): Saskatchewan Department of Mineral Resources Report 55, 27 p.
- Murphy, W.L., 1986, The Star Lake gold deposit, northern Saskatchewan, in L.A. Clark, ed., Gold in the Western Shield: Canadian Institute of Mining and Metallurgy Special Volume 38, p.212 - 220.
- Poulsen, K.H., D.E. Ames, and A.G. Galley, in press, Gold mineralization in the Star Lake Pluton, La Ronge Belt, Saskatchewan: a preliminary report, in Current Research, Geological Survey of Canada, Part A, Paper 86-1A.
- Thomas, D.J., 1984, Geological mapping, Star Lake area, in R. Macdonald and T.I.I. Sibbald, eds., Summary of Investigations 1984, Saskatchewan Geological Survey: Saskatchewan Energy and Mines Miscellaneous Report 84-4, p. 21-31.
- Turner, R.W., 1985, Internal Report, Mallard Zone: Mahogany Minerals Resources Inc.

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REGIONAL GEOCHEMICAL SURVEYS AND GOLD IN LAKE SEDIMENT INVESTIGATIONS IN SASKATCHEWAN

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ABSTRACT

National Geochemical Reconnaissance surveys began in Saskatchewan in 1974 under the Canada - Saskatchewan Agreement on Mineral Exploration and Development and are continuing under the Canada - Saskatchewan Subsidiary Agreement on Mineral Development (1984 - 89). A total of 10,638 centre-lake sediment samples with an average site-density of 1 per 13 km² have been collected from over 137,000 km² of northern Saskatchewan. They have been analysed for some or all of Zn, Cu, Pb, Ni, Co, Ag, Mn, Cd, Fe, Mo, V, As, Hg, U, LOI, F, Sb, and Au. Near-surface lake waters, collected from 6,870 sites since 1977, have been analysed for U, F and pH. Regional compilations of moving-average geochemical trend maps delineate high concentrations in the underlying bedrock, and in other instances may reflect areas of enhanced economic mineral potential (e.g. elevated U, Cu, Ni and Au in Aphebian supracrustal belts).*

In 1984, gold analyses were undertaken on over 3,500 archived lake sediment samples collected during the 1974 regional survey of the southeastern Saskatchewan Shield area (Geological Survey of Canada, 1985b). Anomalous concentrations of Au were found along the length of the La Ronge Domain, in the eastern Flin Flon Domain, throughout part of the Glennie Lake Domain, and in parts of the Wathaman Batholith. These data suggest that gold-bearing potential exists in lithostructural units outside Aphebian supracrustal sequences. Release of this information has prompted the mineral industry to acquire nearly 68,900 ha of new mineral claims.

Geochemical follow-up studies of anomalous concentrations of Au in lake sediments were initiated in the Waddy Lake area and the Chancellor - Karos Lakes area of the La Ronge Domain in 1985:

- 1) In Waddy Lake, loss-on-ignition (LOI) values are typically less than 12 per cent, and Au values range from less than 1 to 65 ppb. Clusters of anomalous Au values were found in lake sediments adjacent to known Au occurrences. Waddy Lake data suggest that at least some of the variability in Au concentration may be attributed to this metal's presence to some extent in particulate form.*
- 2) Lake sediments in the Chancellor Lake area have LOI values ranging from 2 per cent to 50 per cent, and Au values ranging from less than 1 to 49 ppb. Sandy tills with Au concentrations up to 15 ppb were identified adjacent to Chancellor Lake.*
- 3) Lake sediment samples collected from Karos Lake, where a 386 ppb Au value was reported (Geological Survey of Canada, 1985b), have LOI values generally less than 20 per cent and returned Au values less than 2 ppb. Gold-concentration variability in Karos Lake may represent an extreme case of the particle-sparsity effect resulting from particulate Au.*
- 4) Elsewhere, anomalous Au values in lake sediments were identified adjacent to basic volcanic rocks of the La Ronge belt southeast of Eyaapo Lake.*

Regional and follow-up geochemical data indicate that Au distribution in lake sediments is influenced to a much greater degree by bedrock composition, mineralization, and glacial till than by LOI, Fe and Mn levels.

* LOI: Loss on ignition.

INTRODUCTION

Regional geochemical data, an important component of Canada's mineral resource appraisal and environmental assessment, assist in the detection of mineral deposits and further the understanding of the crustal distribution and secondary dispersion of elements with economic merit.

Since 1972, the Geological Survey of Canada has carried out large-scale reconnaissance collection of lake sediments to

evaluate the mineral-resource potential of the Canadian Shield. To date, the National Geochemical Reconnaissance (NGR) Program has resulted in the collection of about 66,900 centre-lake bottom-sediment samples from approximately 944,400 km² of Precambrian Shield (Lund, in prep.).

This paper summarizes the status of the National Geochemical Reconnaissance Program in Saskatchewan, reviews regional gold in lake sediment data from the southern Shield in the province, and presents preliminary results of follow-up

geochemical sampling related to gold in lake sediments from the La Ronge Domain.

Regional lake sediment and water surveys began in Saskatchewan in 1974 under the Canada - Saskatchewan Agreement on Mineral Exploration and Development, continued in 1977 and 1978 under the Uranium Reconnaissance Program (1975-79), and are presently ongoing as part of the Canada - Saskatchewan Subsidiary Agreement on Mineral Development (1984-89). To date, 10,638 centre-lake sediments (giving an average site density of 1 per 13 km²) have been collected from over 137,000 km² of northern Saskatchewan. They have been analysed for some or all of Zn, Cu, Pb, Ni, Co, Ag, Mn, Cd, Fe, Mo, V, As, Hg, U, LOI, F, Sb and Au. In addition, 6,870 near-surface lake waters collected since 1977 have been analysed for U, F and pH. Figure 1 shows the extent of NGR survey coverage in Saskatchewan, while Table 1 lists the details of each survey. Detailed descriptions of NGR sample-collection and field-data-acquisition methods, sample-preparation and analytical methods, and data-compilation and map-production methodologies are provided by Garrett (1974), Hornbrook and Garrett (1976), and Geological Survey of Canada (1986).

In 1985, detailed geochemical follow-up studies of the NGR gold data were initiated in order to provide a better understanding of the factors which influence the distribution and concentration of Au and its pathfinder elements in various lake sediment environments. The ultimate aim of these studies is to improve field methodology and interpretation of this geochemical exploration technique.

REGIONAL DISTRIBUTION OF GOLD IN LAKE SEDIMENTS FROM EAST-CENTRAL SASKATCHEWAN

In 1984, gold analyses were performed on 3,512 centre-lake sediment samples, collected from 51,000 km² of east-central Saskatchewan and released as Open File 1129 (Geological Survey of Canada, 1985b; see Fig. 1). Lake sediment samples were originally obtained during a regional geochemical reconnaissance survey conducted in 1974 under the Canada - Saskatchewan Agreement on Mineral Exploration and Development. The results of previous multi-element analyses performed on these samples were released as Open Files 266, 488 and 683 (Hornbrook et al, 1975, 1977; Geological Survey of Canada, 1981), and reviewed by Hornbrook and Garrett (1976) and Coker et al (1982). The original lake sediment samples have now been analysed for Zn, Cu, Pb, Ni, Co, Ag, Mn, As, Mo, Fe, Hg, LOI (loss-on-ignition), U (fluorometric), U (delayed-neutron counting), and Au. Gold was determined by a fire assay - neutron activation method, using a five- or ten-gram sample depending on the amount of archived material available. Precision and accuracy were monitored using a standard method employed by the GSC as described by Hornbrook and Garrett (1976). Analytical methods for the other geochemical variables are documented in Open File 1129 (Geological Survey of Canada, 1985b).

Release of Open File 1129 in May, 1985 resulted in the staking of 68,900 ha of new mineral properties (Gracie, 1985). Follow-up exploration activity has been initiated on these claims, but results have not yet been assessed. Follow-up geochemical investigations were also carried out by Dunn (1985), Schmitt (1985), and Sibbald and Thomas (pers. comm., 1986).

The Open File survey area lies within the Hudsonian mobile zone of southwestern Churchill Province of the Canadian

Shield. It contains stratigraphically complex, deformed and metamorphosed Archean and Aphebian supracrustal rocks and granitoid plutons (Lewry et al, 1978, 1985) which were affected by the Hudsonian Orogeny (ca. 1.75 to 2.0 Ga, Stockwell, 1982). Five distinct lithostructural domains outlined within the geochemical survey area (Fig. 2) are:

- 1) the Flin Flon Domain (volcanic-arc complex);
- 2) the Kiseeynew Domain (metasedimentary gneisses);
- 3) the Glennie Lake Domain (orthogneiss complex intermixed with subordinate Aphebian metavolcanics and metasediments);
- 4) the La Ronge Domain (volcanic-arc complex flanked by arc-derived metasediments); and
- 5) the Rottenstone Domain (tonalitic gneiss - migmatite complex in the east, granitoid complex in the west).

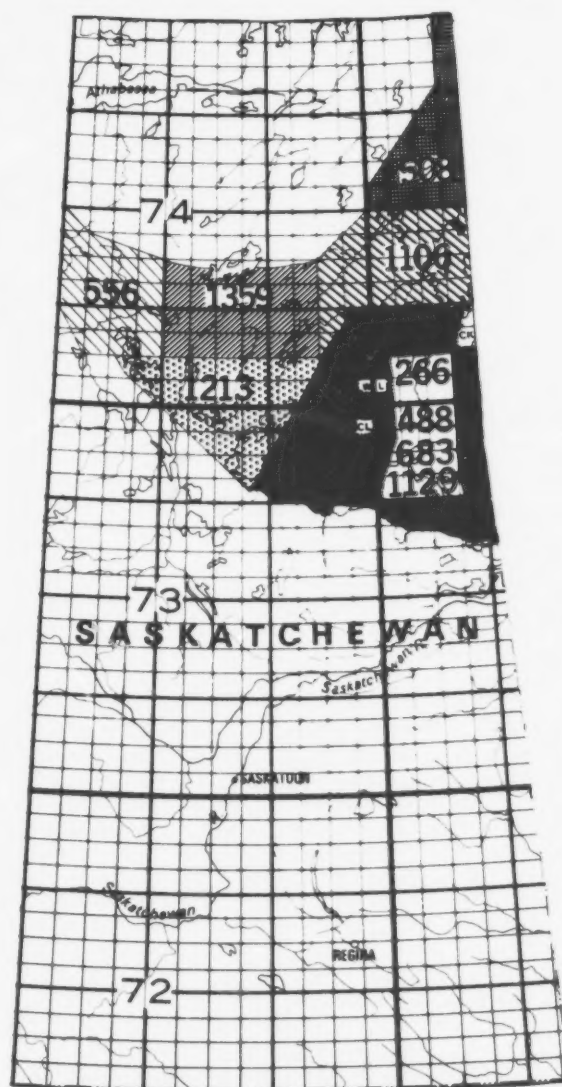


Figure 1. National Geochemical Reconnaissance lake sediment and water surveys in Saskatchewan. Bold numbers refer to GSC Open File Reports. Geochemical follow-up areas for Au are indicated as: WL — Waddy Lake, CK — Chancellor-Karos, CL — Colin Lake.

Mineral-deposit types occurring within the survey areas include: gold-bearing quartz veins or pyritic shear zones, spatially related to volcanic arc and felsic intrusive environments (Johnston, 1981; Pearson, 1981, 1983; Poulsen et al, 1985); sulphide-facies iron formation with variable Cu, Zn, Pb, Cd, Au, Ag, Te, and Se associated with volcanics, graphitic pelites, and tuffaceous metasediments (Sangster, 1978; Harper, 1983); Cu- or Ni-bearing sulphides with traces of Au, Ag and PGEs hosted by mafic to ultramafic flows and intrusions (Beck, 1959; Fox and Johnston, 1981; Hulbert, 1985); U- and Mo-bearing granitoids and pegmatites (Cheesman, 1959; Lehto et al, 1976; Gilboy, 1980); and asbestos-bearing and serpentinized ultramafics (Beck, 1959).

The survey area lies within the Kazan Upland physiographic subdivision of the western Canadian Shield drained by the Nelson and Churchill River systems. It is characterized by low, undulating relief and northeasterly elongated drainage basins which reflect the effects of glaciation and underlying bedrock structures. The predominant ice direction in the region was from northeast to southwest. The two predominant glacial landform types include a thin veneer of sandy to clayey lodgement till overlying bedrock, and moderately thick, discontinuous, stratified glaciolacustrine silts and clays related to proglacial Lake Agassiz (10,000 to 8,000 years BP, Langford, 1977; Schreiner, 1984).

REGIONAL GEOCHEMICAL TRENDS

The distribution pattern for Au in lake sediments from the southeastern Precambrian Shield of Saskatchewan is shown in Figure 2. A prominent feature is the regional concentration of elevated Au values in the south and central survey area. Generally, coincident patterns are observed for Cu and As (Hornbrook and Garrett, 1976). The main controlling factor on the regional distribution of these elements appears to be the distribution of supracrustal lithologies (i.e. metavolcanics, metasediments and ultramafics) associated with Aphebian volcanic arcs (Table 2), rather than sympathetic enrichment by

limnological factors such as pH, LOI, Fe and Mn (indicated by low correlations in Table 3).

Areas A, B and C outlined on Figure 2 contain geochemical features discussed below. Area A is the focus of follow-up studies in the Chancellor - Karos Lakes area, Area B contains the Waddy Lake and Colin Lake follow-up areas, and Area C contains regionally developed geochemical trends in the Pelican Narrows area.

Several prominent linear trends of elevated Au concentrations are evident on Figure 2. One trend, nearly 30 kilometres wide and over 120 kilometres long, extends north-northeast from the Lac La Ronge - Nemeiben Lakes area (55° 20' N; 105° W) to the Waddy Lake area (56° 15' N; 103° 50' W). Copper and, to a lesser extent, Hg and As exhibit coincident trends. The multi-element geochemical trend is almost entirely contained within the La Ronge Domain and reflects enhanced background levels in bedrock lithologies characteristic of this volcanic-arc-derived geological environment (Table 2).

The north-central part of this trend, encompassed by Area B (Fig. 2), is displayed as a multi-element (Au-As-Cu) plot in Figure 3. The area straddles the La Ronge Domain and adjacent Rottenstone and Glennie Lake Domains, and exhibits a strong Au-Cu (and spatially related As) trend coincident with the distribution of the central metavolcanic and felsic intrusive rocks (Central Metavolcanic Belt) of within the La Ronge Domain. Major Au $\pm$ Cu $\pm$ As anomalies occur in proximity to known Au-bearing mineral deposits, such as Star and Jojay.

Another cluster of Au-Cu $\pm$ U $\pm$ Mo $\pm$ Ni anomalies occurs east of the central La Ronge volcanic belt in the vicinity of Colin Lake, between 104° W and 104° 30' W, and south of 55° 55' N (Fig. 3). Migmatized greywacke, garnetiferous hornblende gneiss and granitic gneiss of the MacLean Lake Belt (Lewry, 1984) underlie this area of unknown mineralization. Bedrock exposures are widespread except for a thin discontinuous

Table 1. Summary of National Geochemical Reconnaissance surveys in Saskatchewan.

GSC Open File	Release year	NTS map areas whole (partial)	Survey area (km ²)	Number of lake sediment samples	Survey funding*
266 ¹	1975	63M, 64D (63K, 63L, 63N, 73I, 73O, 73P, 74A)	51,000	3,844	1
488 ¹	1977	same as OF 266	51,000	3,844***	1
508 ¹	1978	64L (64M)	11,900	2,019	2
556	1978	(74C, 74F)	15,000	909	2
683 ²	1981	(64D)	6,300	266	3
1106 ²	1985	64E (74A, 74H)	18,800	1,178	4
1129 ²	1985	same as OF 266	51,000	3,512***	4
1213 ²	1986	(73O, 73P, 74A, 74B, 74C)	17,000	1,152	4
1359**	1987	(74A, 74B, 74G, 74H)	17,000	1,270	4

* 1) Canada - Saskatchewan Agreement on Mineral Exploration and Development

2) Canada - Saskatchewan Agreement on a Uranium Reconnaissance Program

3) Geological Survey of Canada

4) Canada - Saskatchewan Subsidiary Agreement on Mineral Development (1984-89).

** Open File 1359 compilation in progress.

*** Further analysis of archived samples (OF 266).

¹ See Hornbrook et al, 1975, 1977, and 1978 for OF 488, OF 266 and OF 508.

² See Geological Survey of Canada, 1981, 1985a, 1985b, and 1986 for OF 683, OF 1106, OF 1129 and OF 1213.

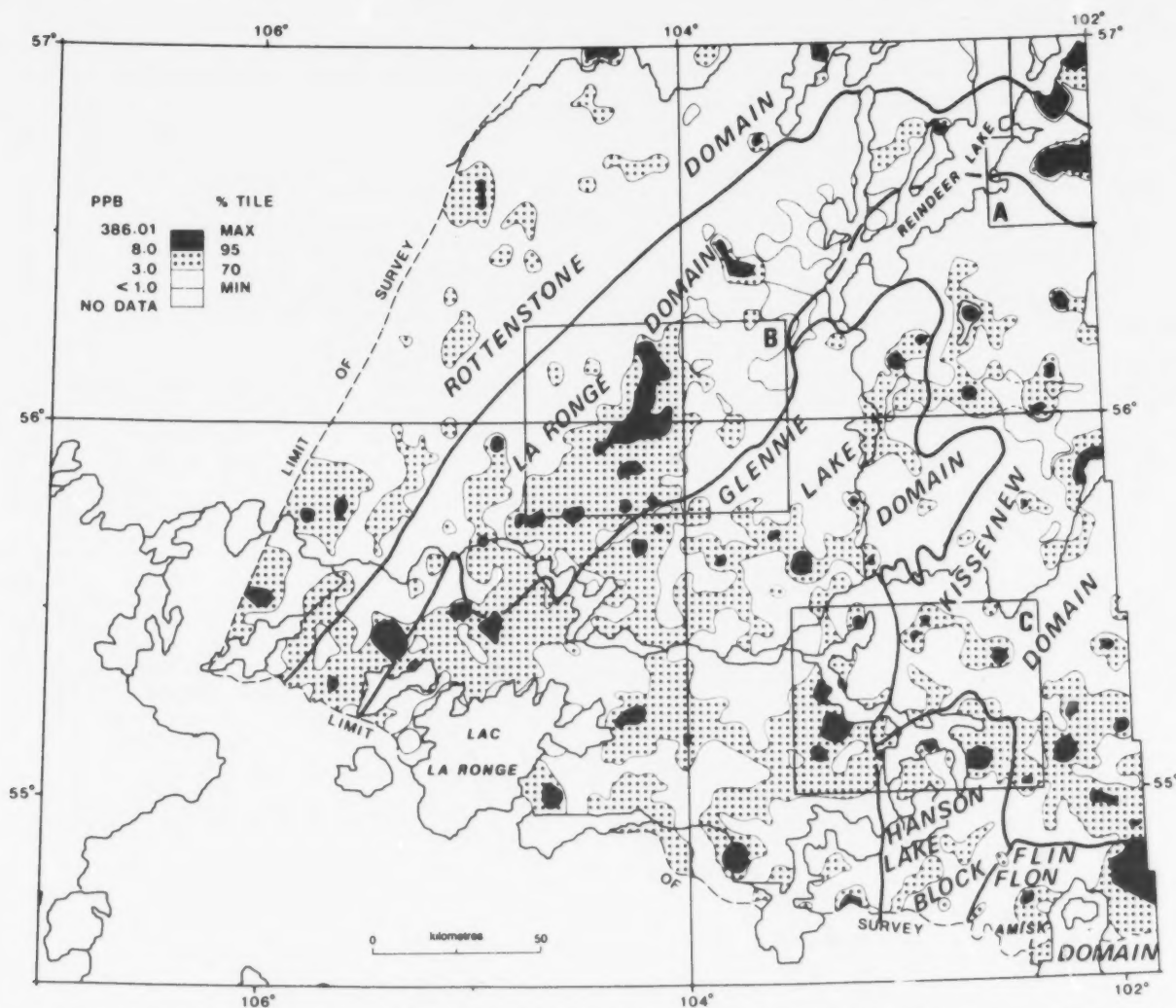


Figure 2. Distribution of 70 and 95 percentile contours of Au in lake sediments from the southeast Precambrian Shield of Saskatchewan: A — Chancellor - Karos Lakes geochemical follow-up area; B — central La Ronge Domain and Waddy Lake follow-up area; C — Pelican Narrows area. Au data from Geological Survey of Canada Regional Geochemical Open File 1129 (Geological Survey of Canada, 1985b).

veneer of locally derived glacial till or localized accumulations of organic-rich material in low-lying areas. To evaluate further this and other geochemical responses occurring in geological environments without reported Au mineralization, a geochemical follow-up study was initiated by Schmitt in 1986; analytical results are pending.

A second prominent regional geochemical trend outlined in Figure 2 extends over 150 kilometres west-northwest from Flin Flon (54° 46' N; 101° 53' W) to the vicinity of Glennie Lake (55° 45' N; 103° 50' W). Nickel, Co, Cu and As exhibit similar regional geochemical patterns in this area, although displaced somewhat to the north. Part of this Au trend from the vicinity of Wildnest Lake (55° N; 102° 20' W) to the Churchill River (55° 20' N; 103° 40' W), cuts across many lithological and regional structural trends, suggesting a possible regional metallogenic association. Figure 4 encompasses about 4,000 km² of this regional trend centred approximately on Pelican Narrows (55° 10' N; 102° 54' W). In the north-central part of the area, coincident Au-As anomalies, numerous As anomalies and scattered U, Mo, Cu, Ni, Pb, and Zn anomalies (refer to

Geological Survey of Canada, 1985b; Lehto et al, 1976) occur over an area of nearly 200 km². Geology of the area is characterized by the Maguire Lake granodiorite pluton as well as by pegmatites, biotite gneisses and migmatites (Lehto et al, 1976; Macdonald, 1981). The north-northeasterly Guillox lineament trends across the northwestern end of the Maguire Lake Pluton. A similar association of the felsic intrusive rocks, northerly trending structures (Poulsen et al, 1985) and Au-As anomalies in lake sediments is an important mineral exploration feature in the Star Lake area of the La Ronge Domain. Although the writers are not aware of mineral occurrences in the Maguire Lake area, the geological associations urge a careful reappraisal of its mineral potential.

DETAILED GEOCHEMICAL FOLLOW-UP STUDIES ON GOLD IN LAKE SEDIMENTS, LA RONGE DOMAIN

Geochemical follow-up and orientation studies were initiated in the La Ronge Domain at Waddy Lake (NTS 64D/4) and

Table 2. Distribution of gold in lake sediments underlain by various lithologies.

Rock Type	Number of analysed samples	Range (ppb)	Samples <1 ppb	Arithmetic* Mean	Standard Deviation	Coefficient of Variation (CV per cent)	95 per cent Confidence Bounds on Arithmetic Mean	Geometric* Mean	Log ₁₀ Standard Deviation	95 per cent Confidence Bounds on Geometric Mean
Amphibolite	279	<1 - 32	84	2.97	3.60	121.5	2.54 - 3.39	1.25	0.97	1.03 - 1.51
Granite	1369	<1 - 88	448	2.75	4.58	166.3	2.51 - 3.00	1.03	0.720	0.95 - 1.13
Meta-arkose	99	<1 - 12	22	2.78	2.34	84.0	2.32 - 3.25	1.48	0.630	1.11 - 1.98
Migmatite	584	<1 - 45	182	2.28	3.17	139.0	2.03 - 2.54	0.90	0.700	0.79 - 1.02
Marble	31	<1 - 18	22	1.39	3.40	244.7	0.14 - 2.64	0.29	0.709	0.16 - 0.52
Metasediment	131	<1 - 23	18	3.79	3.13	82.6	3.25 - 4.33	2.30	0.573	1.83 - 2.88
Metavolcanic	194	<1 - 355	40	6.01	25.7	428.2	2.36 - 9.65	2.02	0.684	1.62 - 2.52
Pelitic Schist	782	<1 - 386	339	3.09	18.0	582.1	1.83 - 4.36	0.77	0.738	0.68 - 0.87
Ultramafic	43	<1 - 37	6	4.52	5.49	121.3	2.84 - 6.21	2.84	0.514	1.97 - 4.09
Total Gold Data Set	3512	<1 - 386	1161	3.0	11.0	367.0	2.63 - 3.36	1.04	0.721	0.98 - 1.10

* Values below detection limit were arbitrarily set to 0.1 ppb for calculating the statistics.

Chancellor - Karos Lakes (NTS 64D/9, 64D/16) in 1985, and continued at Waddy Lake (NTS 64D/4, 74A/1) and commenced at Colin Lake (73P/16) in 1986 (Fig. 1).

WADDY LAKE AREA — NTS 64D/4, 74A/1

The Waddy Lake follow-up area covers over 150 km² situated 160 km northeast of La Ronge. The area was chosen for geochemical follow-up studies because of the widespread occurrence of Au mineralization, favourable geology, and a weak or absent Au response in lake sediments reported in Open File 1129 (Geological Survey of Canada, 1985b) because

of limited archived material. In 1985, field investigations centred on Upper and Lower Waddy Lakes and adjacent mineral occurrences. They involved detailed collection of replicate lake sediments, near-surface lake waters and stream sediments entering Waddy Lake, and litho-geochemical sampling of several gold-bearing mineral occurrences. In 1986, field investigations were expanded westward to Brindson Lake; results are pending.

Recent geological mapping by Harper (1984, 1985) has outlined a complex sequence of northeast-trending metavolcanic and metavolcaniclastic rocks intruded by

Table 3. Correlation Matrix for regional lake sediment data.

	Zn	Cu	Pb	Ni	Co	Ag	Mn	As	Mo	Fe	Hg	LOI	U*	Au
Zn		0.61	0.33	0.62	0.62	0.05	0.38	0.11	0.15	0.51	0.31	0.14	0.17	0.05
Cu	3844		0.15	0.68	0.50	0.02	0.19	0.20	0.17	-0.26	0.40	0.32	0.21	0.20
Pb	2452	2452		0.28	0.29	0.11	0.21	-0.01	-0.02	0.32	0.06	0.26	0.02	0.01
Ni	3832	3831	2451		0.68	-0.01	0.26	0.11	0.01	0.33	0.25	0.01	0.08	0.05
Co	3822	3821	2444	3813		0.09	0.56	0.06	0.15	0.57	0.21	-0.08	0.06	0.03
Ag	1582	1581	1036	1577	1572		0.05	0.01	0.01	0.05	-0.02	-0.03	0.07	0.14
Mn	3845	3844	2452	3832	3822	1582		0.04	0.24	0.64	-0.02	-0.21	0.05	-0.02
As	3227	3226	2196	3220	3212	1376	3227		0.09	0.00	0.25	0.22	-0.02	0.09
Mo	3171	3171	2001	3162	3155	1322	3171	2666		0.16	0.06	0.16	0.14	0.08
Fe	3845	3844	2452	3832	3822	1582	3845	3227	3171		0.04	-0.23	0.05	0.07
Hg	3791	3790	2422	3779	3769	1565	3791	3189	3140	3791		0.40	0.07	0.09
LOI	3839	3838	2447	3826	3816	1580	3839	3222	3167	3839	3785		0.13	0.09
U*	3453	3453	2236	3444	3437	1435	2882	2892	3453	3407	3447	3449		0.01
Au	2398	2397	1645	2395	2388	922	2398	2092	2800	2398	2379	2395	2169	

Upper right: Correlation coefficients calculated using log₁₀ transformed data and deletion of values below detection limit.

Lower left: Number of pairs.

* Uranium: Determined by delayed-neutron activation counting, used in the correlation matrix.

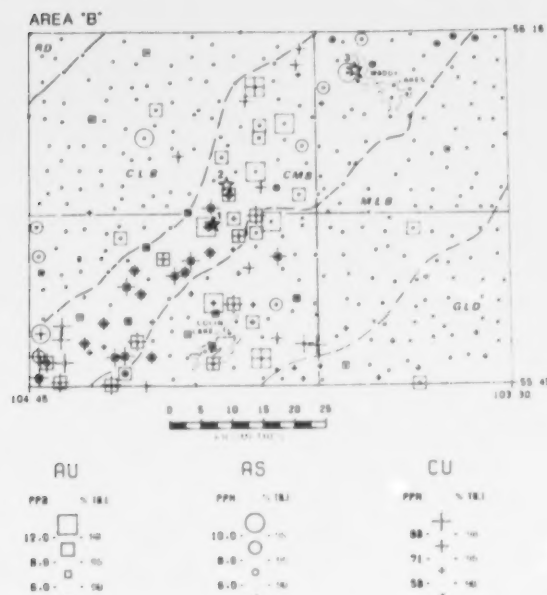


Figure 3. Multi-element symbol plot showing the distribution of Au, As and Cu in lake sediments from the La Ronge Domain, east-central Saskatchewan. RD — Rottenstone Domain; CLB — Crew Lake Belt; CMB — Central Metavolcanic Belt; MLB — MacLean Lake Belt; GLD — Glennie Lake Domain. 1: Starrex Au mine; 2: Jojay Au deposit; 3: Komis Au deposit.

numerous ultramafic to acid plutonic rocks. The Komis gold deposit and other vein- or shear-zone-related Au showings and Au-bearing structures occur in the study area. Mapping of Quaternary stratigraphy by Campbell (1985) at 1:20,000 scale has delineated a complex mosaic of glacial till, glaciofluvial, glaciolacustrine, and organic deposits. Ice directions are most commonly at 190° to 192°.

Lake and stream sediments, and lithogeochemical samples from 1985 have been analysed for Zn, Cu, Pb, Ni, Co, Ag, Mn, Ba, Mo, Fe, Sn, LOI, Hg, As, Sb, U, F, V, Cd, Cr, Sr, W and Au. Near-surface lake waters and stream waters have been analysed for some or all of pH, alkalinity (as ppm CaCO_3), conductivity, F, Cl, Br, PO_4 , NO_3 , SO_4 , Na, K, Ca, Mg, Zn, Mn, Fe, Cu, Pb, Ni, Co, Mo and Au. Compared to regional lake sediment data from east-central Saskatchewan, geometric mean values in Waddy Lake sediments are lower for Zn, Cu, Co, As, Hg, and LOI; higher for Pb and Mn; and similar for Mo, Fe, Ni, U, and Au. A detailed interpretation of element distributions and correlations is underway and will be completed on receipt of 1986 analytical data.

Table 4 summarizes the results of geochemical analyses for Au performed on lake sediments collected in 1985 from Waddy Lake; it also lists Au statistics for regional data from east-central Saskatchewan for comparison.

Lake sediments from Waddy Lake characteristically have a high-silt, low-organic content. Loss-on-ignition (LOI) values, a measure of organic content, ranging from 1.2 per cent to 12.2 per cent, with a geometric mean of 5.1 per cent, are abnormally low when compared to values encountered for organic-rich Shield lakes. For example in east-central Saskatchewan the geometric mean value for LOI on 3,844 lake sediment samples was 22.5 per cent. The silt component of

Waddy Lake sediments is probably derived from the surrounding silty glacial ground moraine and proglacial Lake Agassiz glaciolacustrine and glaciofluvial deposits. Abnormally high Mn values to 20,000 ppm and Fe values up to 12 per cent probably reflect the observed presence of Fe and Mn concretions. Analysis of a composite sample of several dozen Fe-Mn concretions from one site found enrichment in Zn, Pb, Co, Mo, V, As, U and Ni and depletion in Sr, Ba, F and Cr. Analysis of 10 g of concretion material for Au gave a value of 3 ppb, possibly indicating that Au is not appreciably enriched.

The following preliminary observations can be made from Figure 5 which displays the distribution of Au from Waddy Lake:

- 1) gold concentrations in lake sediments range from less than 1 to 65 ppb with a geometric mean of about 1 ppb;
- 2) repeat analyses of replicate samples collected from three 1974 regional lake sediment survey sites reproduced the Au values reported in Open File 1129 (Geological Survey of Canada, 1985b; sites 64D742012, 64D742147, 64D742148); at two other NGR sites (64D742149; 64D741681) analyses from detailed sampling were up to 10 ppb higher;
- 3) clusters of high values occur in lake sediments adjacent to the Waddy gold showing on the western shore of Upper Waddy Lake; weathered tills taken from the area of this showing range up to 285 ppb and probably provide a source for some of the gold in lake sediments; other elevated Au values in lake sediments occur in southern Lower Waddy Lake and may reflect the VG showing or other previously undetected mineralization;

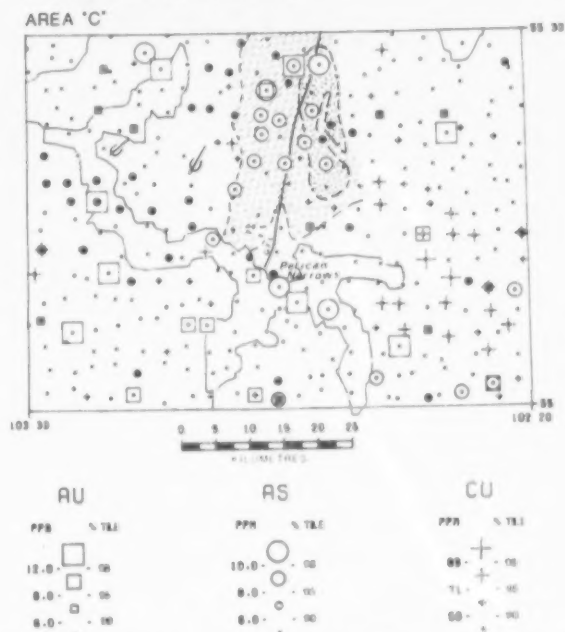


Figure 4. Multi-element symbol plot showing the distribution of Au, As and Cu in lake sediments in the Pelican Narrows area, east-central Saskatchewan. GFL — Guilfoyle lineament. Diagonal dashed pattern — Kisseynew biotite gneisses; random dashed pattern — Maguire Lake granodiorite pluton. Glacial ice directions shown are from Schreiner (1984). Refer to Figure 2 for location relative to Regional Survey.

Table 4. Summary statistics on the distribution of gold (ppb) in lake sediments.

	Regional Survey Open File 1129*	Waddy Lake	Chancellor — Karos Lakes
Number of samples	3512	57	89
Minimum	less than 1	less than 1	less than 1
Maximum	386	65	49
Number of samples less than 1 ppb	1161	21	72
Arithmetic mean [†]	3.0	4.0	less than 1
Arithmetic standard deviation	11.0	9.67	6.71
Geometric mean	1.04	0.9	0.2
Log ₁₀ standard deviation	0.7207	0.8123	0.4903
95th percentile	8.0	11.0	2.0

* Geological Survey of Canada (1985b).

[†] Values below detection level were arbitrarily set to 0.1 ppb for calculating the statistics.

- 4) analyses for Au in one litre near-surface lake waters and stream waters collected from 12 sites in duplicate were consistently less than 1.0 part per trillion except for one sample from the centre of Lower Waddy Lake which gave an anomalous value of 3.8 parts per trillion; and
- 5) gold values for stream sediments collected adjacent to Waddy Lake were 4 ppb to 9 ppb for Round Lake Creek, 4 ppb for the creek draining Byers Fault, and 5 ppb and 79 ppb from a creek 1.2 km south of Byers Fault (Fig. 5); based on a limited number of analyses, background Au concentrations in stream sediments appear to be less than 5 ppb.

CHANCELLOR - KAROS LAKES AREA — NTS 64D/9; 64D/16

The Chancellor - Karos Lakes study area covers nearly 200 km² between Reindeer Lake and the Manitoba border 20 to 50 km south of Kinoosao (Fig. 1). Lake sediment geochemical studies were carried out in 1985 to follow-up several isolated Au anomalies (386 ppb in Karos Lake, 88 ppb from a lake 4 km southwest of Eyaapo Lake), a cluster of Au anomalies ranging up to 32 ppb around Chancellor Lake, and elevated As and Mo values reported in Open File 1129 (Geological Survey of Canada, 1985b).

Field work entailed detailed replicate lake sediment and near-surface water sampling and repeat sampling of 21 NGR sites. A total of 89 sites were sampled, from which 136 lake sediment and 85 near-surface water samples were collected. In addition, several ground traverses were conducted adjacent to Chancellor Lake and several bedrock, till, and stream sediment samples were obtained.

Lake sediments, stream sediments, lithogeochemical samples and near-surface lake waters were analysed for the same geochemical variables as the Waddy Lake area samples. In general, the geometric means for most trace elements are lower than the corresponding means for data from east-central Saskatchewan. However, the upper range of values encountered in the Chancellor - Karos Lakes area commonly exceeds the 95th percentile of regional data.

Widespread bedrock exposures show the study area to be underlain predominantly by dioritic to tonalitic intrusives of



Figure 5. Distribution of Au (ppb) in lake sediments from Waddy Lake. Values followed by an asterisk (*) indicate that analyses were performed on a sample weighing less than 10 g. An asterisk beside a sample site indicates no data. Regional geochemical survey sites are denoted by ■. Location of Komis Au deposit, and of Waddy and VG Au occurrences are indicated by solid black triangles.

the La Ronge Domain, with minor bands of pelitic to psammopelitic metasediment, and basic to intermediate metavolcanic rock. Scattered occurrences of gabbro and pyroxenite are present in the south, whereas pelitic to psammo-pelitic gneiss and migmatite of the Rottenstone Domain occur in the north (Johnston and Thomas, 1984). Pegmatite and aplite dykes are locally abundant. Quaternary deposits include a thin discontinuous veneer of sandy till and local organic deposits with the dominant ice direction from the north-northeast. Mineral occurrences have been neither reported nor discovered during field investigations. Active exploration by several companies is underway on a number of claim blocks, staked after the release of OF 1129 (Geological Survey of Canada, 1985b), in the Eyaapo Lake and Chancellor Lake areas.

RESULTS AND DISCUSSION

Table 4 summarizes the distribution of Au in the Chancellor-Karos Lakes area. Lakes within the study area display a wide range of physical and limnological characteristics. Large lakes in the north, or those which are more than ten metres deep and underlain by dioritic rocks in the south, generally have silt-rich sediments with LOI values less than 25 per cent. Smaller, shallow, organic-rich lakes contain sediments which have LOI values up to 66 per cent and which show a positive correlation with Hg, Cu, U and Zn concentrations.

Figures 6 and 7 display the distribution of gold concentration in lake sediments from Chancellor - Karos Lakes area. The following preliminary observations can be made regarding the distribution of Au:

- 1) gold values range from less than 1 to 49 ppb with a geometric mean less than 1 ppb;
- 2) gold values above detection level were identified from follow-up sampling in three areas: (1) at the north end of Chancellor Lake (56° 42'N; 102° 02'W), where several sites contain 2 to 4 ppb Au adjacent to an NGR site which initially returned a value of 7 ppb Au; two kilometres to the south, between Chancellor Lake and a lake with an NGR site returning 32 ppb Au, unoxidized sandy tills returned initial and repeat values up to 15 ppb Au; (2) west of the southern Chancellor Lake (56° 40'N; 102° 04'W), where one repeat analysis of a 2.5 g sample gave 11 ppb Au from a small lake one kilometre up-ice from replicate NGR sites with 21 ppb and 14 ppb Au; and (3) in a general area three to four kilometres southeast of Eyaapo Lake (56° 40'N; 102° 14'W), where follow-up of an 88 ppb Au NGR site delineated five lakes with elevated Au concentrations up to 49 ppb based on initial and repeat analyses;
- 3) 386 ppb Au NGR site in Karos Lake (56° 50'N; 102° 10'W, Fig. 7) could not be reproduced by repeat sampling; however, adjacent to Karos Lake, Dunn (1985) reported vegetation samples with slight enrichment of Au, Sb and As; and
- 4) south and southeast of Eyaapo Lake, elevated Au, Ni, Cr, Co, and V values occur in organic-rich lakes (LOI 25 to 65 per cent), with low Mn (less than 200 ppm) and Fe (less than 2.5 per cent), adjacent and down-ice from gabbroic and pyroxenitic intrusions; these values are possibly related to compositional differences of catchment basin lithology, and/or previously undetected mineralization.

SUMMARY

National Geochemical Reconnaissance surveys conducted in Saskatchewan between 1974 and 1986 have resulted in the collection of 10,638 centre-lake sediment samples and 6,870 near-surface lake waters from over 137,000 km² of Precambrian Shield terrain. The results of the surveys outline significant regional geochemical trends for several elements of economic merit and have contributed to the exploration and evaluation of Saskatchewan's mineral resources.

Open File 1129 (Geological Survey of Canada, 1985b), which concerns the distribution of Au in lake sediments from over 51,000 km² of east-central Saskatchewan, indicates that the distribution and chemical composition of bedrock lithologies and mineralization are the factors most important in controlling the distribution pattern of Au. Enhanced Au potential is indicated by regionally developed zones of elevated Au $\pm$ Cu $\pm$ Ni $\pm$ As concentration which commonly occur in areas of gold mineralization such as Flin Flon - Schist Lake and the Central Metavolcanic Belt of the La Ronge Domain. Elsewhere, elevated Au values, considered together with other geochemical and geological information, outline prospective areas for mineral exploration.

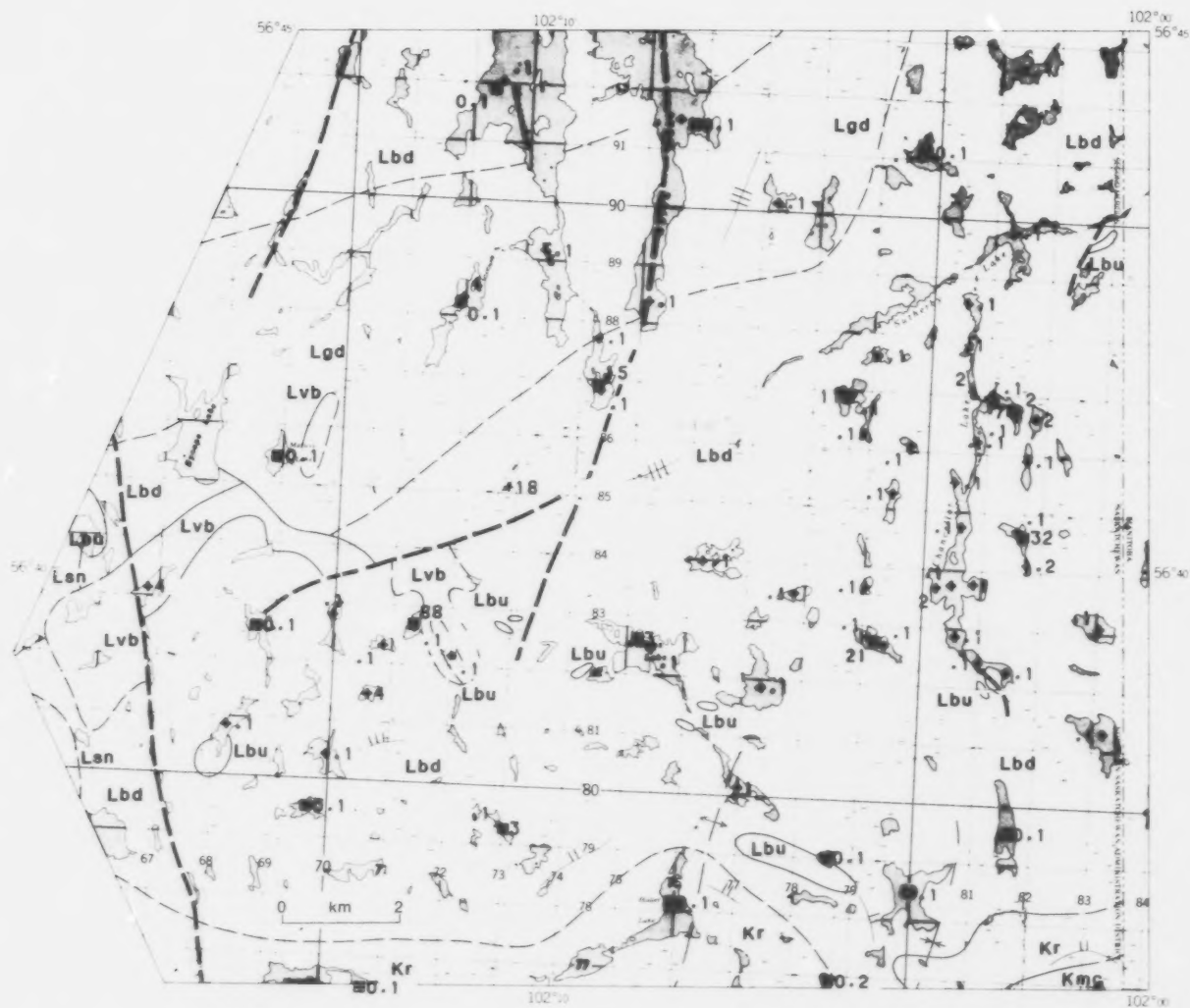
Examination of the regional Au data in relation to other geochemical variables indicates that neither sorption and coprecipitation activity by hydrous Fe and Mn oxides, nor variations in lake sediment organic content (LOI) play major roles in influencing the distribution of Au in the lake sediment environment from the regional survey area. While this may be partially attributable to low Au concentrations available for complexing, it does suggest that Au anomalies have a high probability of reflecting actual enhanced concentration of the metal in a primary surficial or bedrock source within the catchment basin of the anomalous lake, as opposed to false anomalies which may occur for other trace elements that experience sympathetic enrichment by limnological factors.

In Waddy Lake, Au values up to 65 ppb were detected in lake sediments adjacent to known gold mineralization. The abnormally low LOI nature of Waddy Lake sediments and some variability in Au analyses suggest that at least some of the variability in Au concentrations is related to the presence of micron-size particulate Au which has exerted a pronounced particle sparsity effect on geochemical analyses.

In the Chancellor - Karos Lakes area, elevated concentrations of Au up to 49 ppb were identified near anomalous NGR sites in two areas at Chancellor Lake and southeast of Eyaapo Lake. Southeast of Eyaapo Lake, elevated Au, Co, Ni, V and Cr in lake sediments adjacent to basic metavolcanics appear to reflect high-background bedrock concentrations or potential for undiscovered mineralization.

REFERENCES

- Beck, L.S., 1959, Mineral occurrences in the Precambrian of northern Saskatchewan (excluding radioactive minerals): Saskatchewan Department of Mineral Resources Report 36, 135 p.
- Campbell, J.E., 1985, Quaternary geology of the Waddy Lake area applied to prospecting for gold, in R. Macdonald, T.I.I. Sibbald and D.F. Paterson, eds., Summary of Investigations 1985, Saskatchewan Geological Survey: Saskatchewan Energy and Mines Miscellaneous Report 85-4, p. 108-110.



LEGEND

HUDSONIAN

ROTTENSTONE DOMAIN

Rng Pelitic to psammopelitic gneiss and derived migmatite

LA RONGE DOMAIN

Lgd Tonalite, granodiorite, monzogranite

Lbd Diorite, quartz diorite, quartz monzodiorite

Lbu Gabbro, pyroxenite

APHEBIAN

La Ronge Group

Lsn Pelitic to psammopelitic metasediment

Lvb Basic to intermediate metavolcanic rock

KISSEYNEW DOMAIN

Kr Psammitic to psammopelitic gneiss and derived migmatite

Kmc Hornblende gneiss, calc-silicate gneiss, amphibolite

Geological boundary (defined, approximate or inferred)

Structural lineament or possible fault

Major fold axial trace: antiform, synform (approximate)

Structural trend lines interpreted from airphotos and orientation data: (moderate 30 - 59°, steep 60 - 84°, subvertical 85 - 90°)

Geology after W.G.Q. Johnston and M.W. Thomas, 1984, and M.W. Pyke, 1960

Figure 6. Distribution of Au (ppb) in lake sediments from the Chancellor Lake area, NTS 64D/9. Values followed by an asterisk (*) indicate that analyses were performed on a sample weighing less than 10 g. Regional geochemical sample sites denoted by ■.

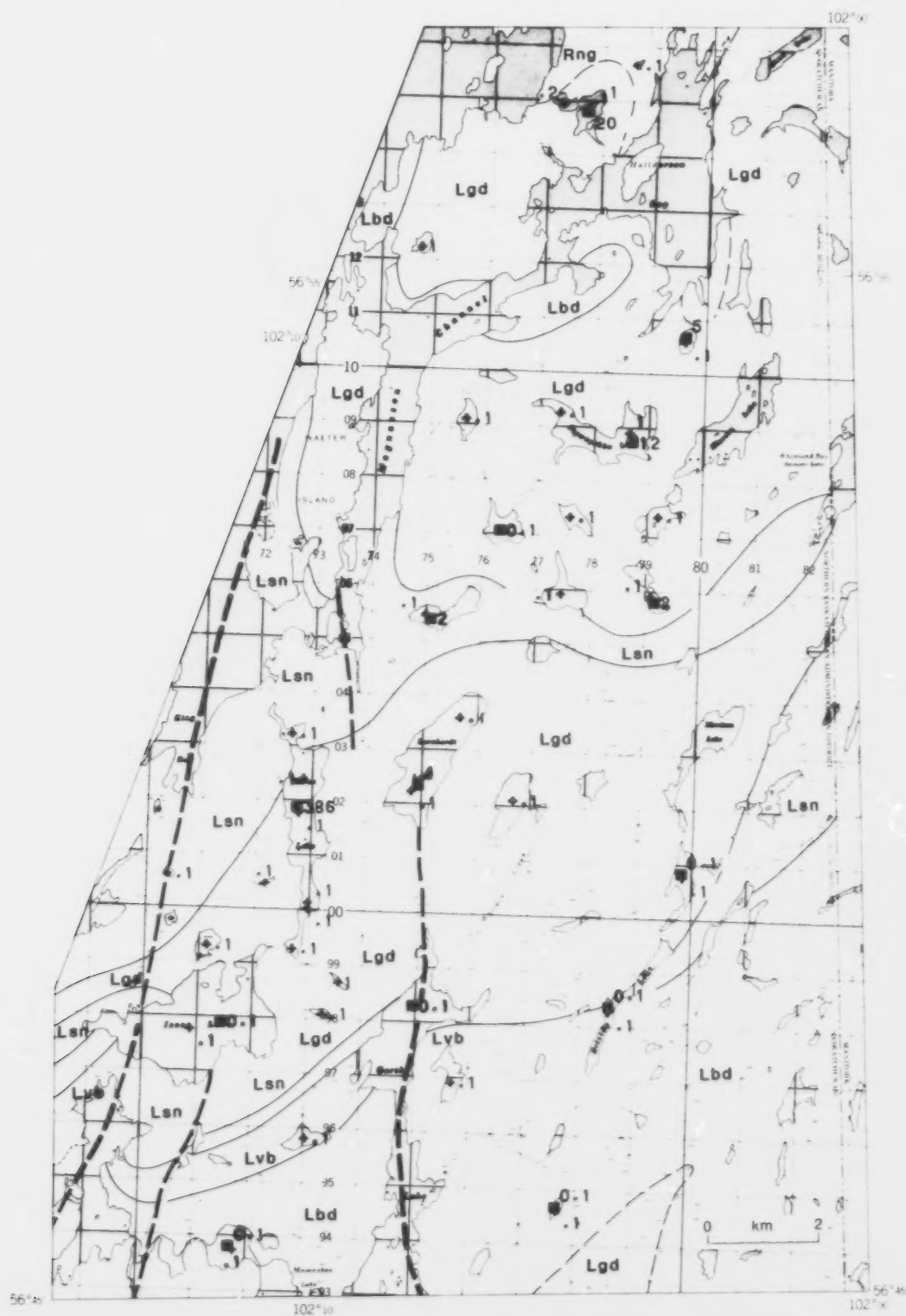


Figure 7. Distribution of Au (ppb) in lake sediments from Karos Lake area, NTS 64D/16. Values followed by an asterisk (*) indicate that analyses were performed on a sample weighing less than 10 g. Regional geochemical samples denoted by ■. See Figure 6 for geological legend.

- Cheesman, R.L., 1959, The geology of the Wapusk Bay Area (west half): Saskatchewan Department of Mineral Resources Report 35, 22 p.
- Coker, W.B., J.S. Fox, and V.J. Sopuck, 1982, Organic centre-lake sediments — Application in the geochemical exploration for gold in the Canadian Shield of Saskatchewan, in R.W. Hodder and W. Petruk, eds., *Geology of Canadian Gold Deposits*, Canadian Institute of Mining and Metallurgy Special Volume 24, p. 267-280.
- Dunn, C.E., 1985, Biogeochemical exploration for gold in the La Ronge Belt, 1985, in R. Macdonald, T.I.I. Sibbald and D.F. Paterson, eds., *Summary of Investigations 1985*, Saskatchewan Geological Survey: Saskatchewan Energy and Mines Miscellaneous Report 85-4, p. 37-49.
- Fox, J.S., and W.G.Q. Johnston, 1981, Komatiites, "boninites" and tholeiitic picrites in the central La Ronge metavolcanic belt, Saskatchewan and Manitoba, and their possible economic significance: Canadian Institute of Mining and Metallurgy Bulletin, v. 74 (831), p. 73-82.
- Garrett, R.G., 1974, Field data acquisition methods for applied geochemical surveys at the Geological Survey of Canada: Geological Survey of Canada Paper 74-52, 36 p.
- Geological Survey of Canada, 1981, Gold in lake sediments (part of NTS 64D) regional lake sediment geochemical reconnaissance data, east-central Saskatchewan: Geological Survey of Canada Open File 683, 16 p.
- Geological Survey of Canada, 1985a, Regional lake sediment and water geochemical reconnaissance data, Saskatchewan (NTS 64E, parts of 74A, H): Geological Survey of Canada Open File 1106, 20 maps, 90 p.
- Geological Survey of Canada, 1985b, Regional lake sediment geochemical reconnaissance data, east-central Saskatchewan (NTS 63M, 64D; parts of 63K, 63L, 63N, 73I, 73O, 73P and 74A): Geological Survey of Canada Open File 1129, 8 maps, 145 p.
- Geological Survey of Canada, 1986, Regional lake sediment and water geochemical reconnaissance data, Saskatchewan (parts of NTS 73P; 74A, B, C): Geological Survey of Canada Open File 1213, 20 maps, 70 p.
- Gilboy, C.F., 1980, Geology of the Reindeer Lake south (southeast) area: Saskatchewan Department of Mineral Resources Report 198, 62 p.
- Gracie, A.J., 1985, Mineral exploration activity in the La Ronge and Athabasca mining districts, in R. Macdonald, T.I.I. Sibbald and D.F. Paterson, eds., *Summary of Investigations 1985*, Saskatchewan Geological Survey: Saskatchewan Energy and Mines Miscellaneous Report 85-4, p. 158-161.
- Harper, C.T., 1983, Iron ores of northern Saskatchewan: Saskatchewan Energy and Mines Report 220, 103 p.
- Harper, C.T., 1984, Geological mapping, Waddy Lake area (part of NTS 64D-4 and 5), in R. Macdonald and T.I.I. Sibbald, eds., *Summary of Investigations 1984*, Saskatchewan Geological Survey: Saskatchewan Energy and Mines Miscellaneous Report 84-4, p. 37-49.
- Harper, C.T., 1985, Bedrock geological mapping, Waddy - Tower Lakes area (part of NTS 64D-4 and 5 and 74A-1 and 8), in R. Macdonald, T.I.I. Sibbald and D.F. Paterson, eds., *Summary of Investigations 1985*, Saskatchewan Geological Survey: Saskatchewan Energy and Mines Miscellaneous Report 85-4, p. 6-17.
- Hornbrook, E.H.W., and R.G. Garrett, 1976, Regional geochemical lake sediment survey, east-central Saskatchewan: Geological Survey of Canada Paper 75-41, 20 p.
- Hornbrook, E.H.W., R.G. Garrett, J.J. Lynch, and L.S. Beck, 1975, Regional geochemical lake sediment reconnaissance data, east-central Saskatchewan (NTS 63M, 64D; parts of 63K, 63L, 63N, 73I, 73O, 73P and 74A): Geological Survey of Canada Open File 266, 52 maps, 108 p.
- Hornbrook, E.H.W., R.G. Garrett, J.J. Lynch, and L.S. Beck, 1977, Regional geochemical lake sediment reconnaissance data, east-central Saskatchewan (NTS 63M, 64D; parts of 63K, 63L, 63N, 73I, 73O, 73P and 74A): Geological Survey of Canada Open File 488, 7 maps, 164 p.
- Hornbrook, E.H.W., J.J. Lynch, and N.G. Lund, 1978, Regional lake sediment and water geochemical reconnaissance data, northeastern Saskatchewan (NTS 64L, 64M (E/4)): Geological Survey of Canada Open File 508, 17 maps, 224 p.
- Hulbert, L., 1985, Ni-Cu-PGE mineralization associated with the Rottenstone Lake harzburgite-pyroxenite intrusion, Saskatchewan: preliminary findings, in R. Macdonald, T.I.I. Sibbald and D.F. Paterson, eds., *Summary of Investigations 1985*, Saskatchewan Geological Survey: Saskatchewan Energy and Mines Miscellaneous Report 85-4, p. 101-102.
- Johnston, W.G.Q., 1981, Gold metallogenic studies: Waddy Lake and region, in J.E. Christopher and R. Macdonald, eds., *Summary of Investigations 1981*, Saskatchewan Geological Survey: Saskatchewan Mineral Resources Miscellaneous Report 81-4, p. 92-96.
- Johnston, W.G.Q., and M.W. Thomas, 1984, Compilation bedrock geology, Reindeer Lake South, NTS 64D: Saskatchewan Energy and Mines Report 230 (1:250,000 scale map with marginal notes).
- Langford, F.F., 1977, Northern extent of Lake Agassiz in eastern Saskatchewan: Canadian Journal of Earth Sciences, v. 14, p. 1286-1291.
- Lehto, D.A.W., R.G. Arnold, and J.W.J. Smith, 1976, Lake sediments as media for exploration in Saskatchewan, in C.E. Dunn, ed., *Uranium in Saskatchewan*: Saskatchewan Geological Society Special Publication 3, p. 100-124.

- Lewry, J.F., 1984, Compilation bedrock geology: Lac La Ronge and Wapawekka areas (NTS 73P/731) - Preliminary geological map - scale 1:250,000, in R. Macdonald and T.I.I. Sibbald, eds., Summary of Investigations 1984, Saskatchewan Geological Survey: Saskatchewan Energy and Mines Miscellaneous Report 84-4.
- Lewry, J.F., T.I.I. Sibbald, and D.J. Rees, 1978, Metamorphic patterns and their relation to tectonism and plutonism in Churchill Province in northern Saskatchewan, in J.A. Fraser and W.W. Hayward, eds., Metamorphism in the Canadian Shield: Geological Survey of Canada Paper 78-10, p. 139-154.
- Lewry, J.F., T.I.I. Sibbald and D.C.P. Schledewitz, 1985, Variation in character of Archean rocks in the western Churchill Province and its significance, in L.D. Ayres, P.C. Thurston, K.D. Card and W. Weber, eds., Evolution of Archean supracrustal sequences: Geological Association of Canada Special Paper 28, p. 239-261.
- Lund, N.G., in prep., Index to open file publications and summary of geochemical reconnaissance surveys in Canada, 1973 - 1986: Geological Survey of Canada forthcoming paper.
- Macdonald, R., 1981, Compilation bedrock geology: Pelican Narrows and Amisk Lake areas (NTS 63M, 63L, and part of 63N and 63K) - Preliminary geological map, scale 1:250,000, in J.E. Christopher and R. Macdonald, eds., Summary of Investigations 1981, Saskatchewan Geological Survey: Saskatchewan Mineral Resources Miscellaneous Report 81-4.
- Pearson, J.G., 1981, Gold metallogenic studies — Phantom-Schist Lake area, in J.E. Christopher and R. Macdonald, eds., Summary of Investigations 1981, Saskatchewan Geological Survey: Saskatchewan Mineral Resources Miscellaneous Report 81-4, p. 97-100.
- Pearson, J.G., 1983, Gold metallogenic studies — Flin Flon - Amisk Lake area, in R. Macdonald, T.I.I. Sibbald, D.F. Paterson and P. Guliov, eds., Summary of Investigations 1983, Saskatchewan Geological Survey: Saskatchewan Energy and Mines Miscellaneous Report 83-4, p.67-74.
- Poulsen, K.H., D.E. Ames, and A. Galley, 1985, Structural studies of gold mineralization in the La Ronge area, in R. Macdonald, T.I.I. Sibbald and D.F. Paterson, eds., Summary of Investigations 1985, Saskatchewan Geological Survey: Saskatchewan Energy and Mines Miscellaneous Report 85-4, p. 96-98.
- Pyke, M.W., 1960, The geology of the Wapus Bay area (east half), Saskatchewan: Saskatchewan Department of Mineral Resources Report 40, 32 p.
- Sangster, D.F., 1978, Isotopic studies of ore-leads of the circum - Kiseynew volcanic belt of Manitoba and Saskatchewan: Canadian Journal of Earth Sciences, v. 15, p. 1112-1121.
- Schmitt, H.R., 1985, Geochemical follow-up studies of gold in lake sediments, in R. Macdonald, T.I.I. Sibbald and D.F. Paterson, eds., Summary of Investigations 1985, Saskatchewan Geological Survey: Saskatchewan Energy and Mines Miscellaneous Report 85-4, p. 94-95.
- Schreiner, B.T., 1984, Quarternary geology of the Precambrian Shield, Saskatchewan: Saskatchewan Energy and Mines Report 221, 106 p. accompanied by 1:1,000,000 map.
- Stockwell, C.H., 1982, Proposals for time classification and correlation of Precambrian rocks and events in Canada and adjacent areas of the Canadian Shield - Part 1: A time classification of Precambrian rocks and events: Geological Survey of Canada Paper 80-19, 135 p.

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THE EAGLE POINT URANIUM DEPOSITS, NORTHERN SASKATCHEWAN

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ABSTRACT

The Eagle Point uranium deposits are located on the eastern edge of the Athabasca Basin, about twelve kilometres north-northeast of the Rabbit Lake mill complex in northern Saskatchewan. They consist of the Eagle North deposit (held by an equal-share joint venture of Eldorado Resources Limited, Noranda Exploration Company Ltd. and Saskatchewan Mining Development Corporation) and the Eagle South deposit (held wholly by Eldorado Resources Limited).

These deposits were discovered in 1980 by Gulf Minerals Canada Ltd. during systematic drill testing of geophysical and uranium-in-till anomalies associated with the Collins Bay Fault northeast along strike from the Collins Bay B-Zone, D-Zone, and A-Zone uranium deposits. Their reserves have been further outlined and significantly increased as a result of drilling during 1985 and 1986.

The Eagle Point deposits consist of a series of moderately steeply dipping tabular veins and lenses which are both concordant and discordant to, and wholly within, Aphebian metamorphic rocks. The mineralization outlined to date occurs entirely within the hanging wall of the Collins Bay Fault.

The deposits lie within the variably graphitic lowest unit of the Aphebian Wollaston Group, and within 5 feet (1.5 metres) to more than 1200 feet (365 metres) of the underlying, possibly Archean granitoid.

Mineralization is considered to be mainly structurally controlled. This conclusion is based in part on the discordant nature of the veins, the presence of microstructures within the veins, and the lack of any consistent association between mineralization and lithology.

Mineralization consists of uraninite and pitchblende, and has been dated at 1400 ± 25 Ma, with younger generations recognized. Only minor amounts of some other metals are present.

The alteration associated with the mineralization is moderately to strongly developed, and consists mainly of illitization. Zones of intense alteration extend less than one metre from mineralization. Hematite is spatially associated with much of the mineralization.

The structures that appear to have primarily controlled the movement of the mineralizing fluids are:

- 1) a series of shear zones trending northeasterly, subparallel to and most probably coeval with the Collins Bay Fault, and*
- 2) one or more steeply dipping tensional(?) fracture systems which have an easterly strike.*

The combined deposits are currently estimated to contain in excess of 140 million pounds U₃O₈. The origin of the deposits remains speculative at this time.

INTRODUCTION

The Eagle Point uranium deposits are situated on the eastern edge of the Athabasca Basin, about twelve kilometres north-northeast of the Rabbit Lake mill complex in northern Saskatchewan, at about latitude $58^{\circ}17.5'$ north and longitude $103^{\circ}36.5'$ west (Fig. 1). They consist of the Eagle North deposit (held by an equal-share joint venture of Eldorado Resources Limited, Noranda Exploration Company Ltd., and

the Saskatchewan Mining Development Corporation) and the Eagle South deposit (held wholly by Eldorado Resources Limited).

The Eagle Point deposits are in close proximity to the Rabbit Lake and Collins Bay B-Zone Mines and the D- and A-Zone deposits. Located on the northwest shore of Harrison Peninsula, the Eagle North deposit lies entirely under the waters of Collins Bay; the Eagle South deposit straddles the shoreline of Collins Bay.

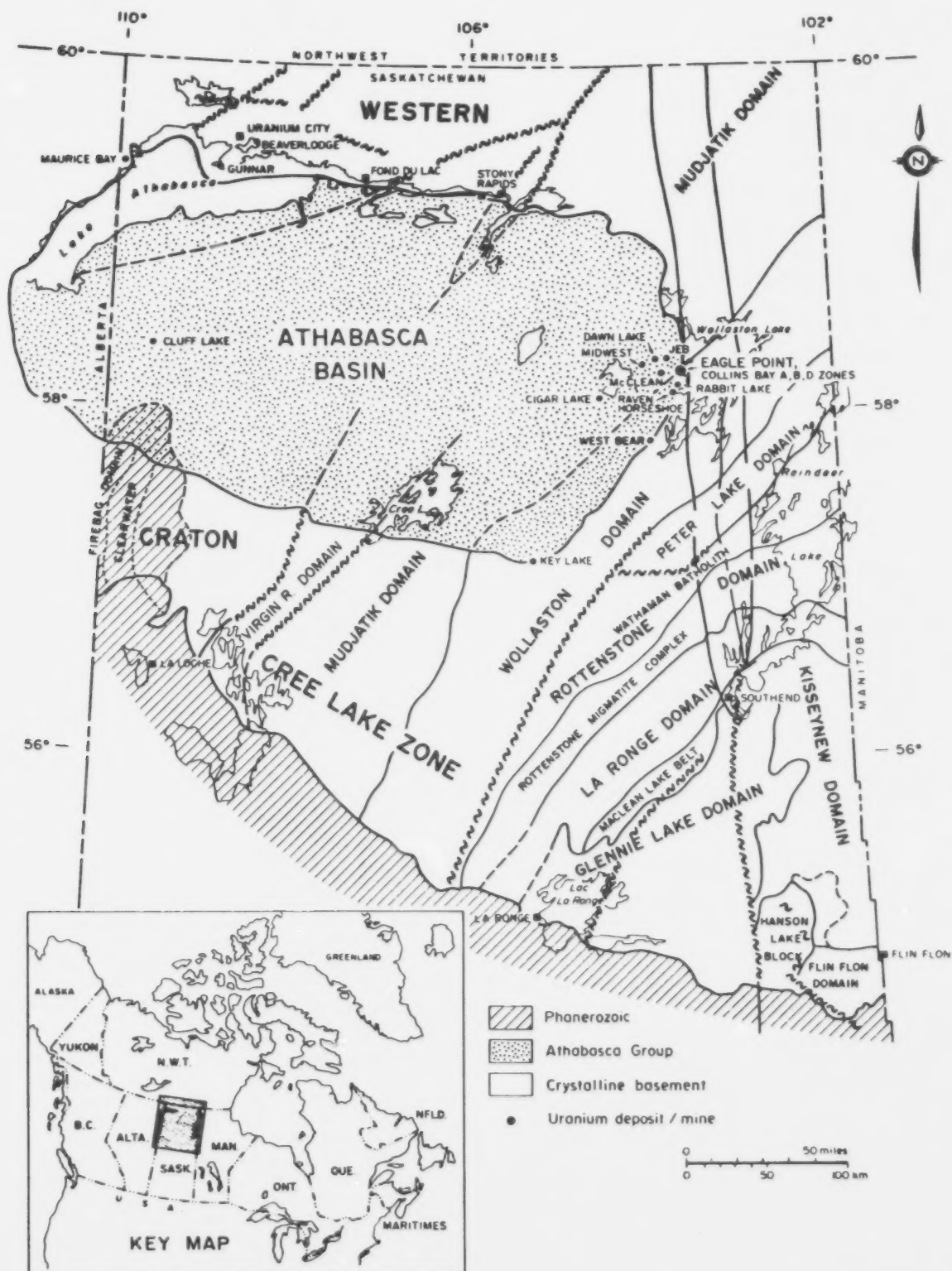


Figure 1. Map showing the major uranium deposits and lithostructural subdivisions of northern Saskatchewan's Precambrian Shield. Modified after Sibbald (1983).

The geological interpretation presented here is based on drill-hole information as no outcrops exist in the Eagle Point area.

The regional geological setting and exploration history are first described. The deposits' geology and their structural and alteration aspects, are discussed next. The paper ends with a summary of the mineralization and reserves.

Considerably more work is required with respect to the geotechnical aspects of Eagle Point. Consequently, this paper should be considered as an interim report only.

GEOLOGY OF THE RABBIT LAKE — COLLINS BAY AREA

The deposits occur within the Wollaston Group of Aphebian age, which lies within the lithostructurally defined Wollaston Domain of the Churchill Province (Fig. 1; Sibbald, 1983). The Wollaston Group overlies a presumed Archean (?) granitoid basement.

A regionally consistent stratigraphy has been established for the Wollaston Domain. It has been recognized in the Rabbit Lake area (Figs. 2 and 3) by Ray (1978), Thomas (1982), Sibbald (1983) and others. The geology of the Rabbit Lake — Collins Bay area is summarized as follows:

STRATIGRAPHY

Archean basement in the Wollaston Lake area may be represented by the Trout Narrows and Berman Island Granites at the south end of Wollaston Lake, and by the Shaganappie Island Granite in the northeast corner of the lake (Sibbald, 1983). In the Rabbit Lake area, a medium- to coarse-grained, foliated to gneissic granitoid unit occurs in a stratigraphic position which is apparently analagous to that of these possibly Archean granites of Wollaston Lake. In places, it underlies, in partial fault contact, variably graphitic Aphebian paragneiss; in other places, it is unconformably overlain by Athabasca sandstone and conglomerate in the footwall of the Collins Bay Fault.

The lowermost section of the Wollaston Group consists of a variably graphitic ferromagnesian-mineral-rich (generally biotite and cordierite) unit, with discontinuous quartzofeldspathic, quartzitic, and/or calc-silicate-bearing interbeds and lenses.

This basal unit hosts the Collins Bay A-, B-, and D-Zone deposits, as well as the Eagle Point deposits. It is overlain by a series of calcareous and non-calcareous metasediments, interlayered with less extensive calc-silicates, plagioclases, and biotitic paragneisses. This succession is marked in its upper part by the appearance of massive carbonate, and was the host for the Rabbit Lake deposit (Heine, 1986; Hoeve and Sibbald, 1978). It is, in turn, overlain by an assemblage of interlayered feldspathic paragneisses, amphibolites, quartzites, and ferromagnesian-mineral-rich metasediments — the Hidden Bay assemblage of Wallis (1971) — stratigraphically the highest rocks yet recognized in the Wollaston Group in Saskatchewan.

The Wollaston Group represents sediments which were deposited in a shallow, marine, near-shore and possibly restricted environment. The carbonates may originally have been algal-bank accumulations, with graphite in some of the

units derived from organic debris. The unusual chemistry of the plagioclases (albite-rich metasediments) suggests that they were derived from saliferous pelites (Appleyard, 1981).

The Hudsonian Orogeny (dated at about 1850 to 1700 Ma) was followed by a long period of erosion of the Aphebian rocks. This conclusion is supported by the presence of a regionally developed paleoweathering zone, well preserved under the Athabasca Group (Macdonald, 1980). Macdonald (1980) has stated that, depending on the host lithology and local dilatency, the thickness of the altered zone ranges from 20 ft (6 m) to 725 ft (220 m) and averages about 100 ft (30 m). This paleoweathering zone is well exposed in the Rabbit Lake pit, in the footwall of the Rabbit Lake Fault.

The Helikian Athabasca Group, deposited between 1430 to 1550 Ma (Langford, 1986), occurs only in the footwall of the Rabbit Lake Fault in the Rabbit Lake area, and mainly (but not exclusively) in the footwall of the Collins Bay Fault. Only the Manitou Falls Formation B member (Ramaekers, 1983), consisting of interbedded fluvial conglomerate and sandstone, is present in the Rabbit Lake — Collins Bay area.

These sediments are generally well layered at a scale of inches (cm) to feet (m), and consist dominantly of quartz, quartzite grains and pebbles. The layering has a planar character, but small-scale (inches [cm] to tens of inches) crossbeds occur. The coarser grained, conglomeratic layers are typically hematitic, and thin bands of heavy minerals are common.

The Athabasca Group in the Rabbit Lake map area (Fig. 3) is about 300 feet (90 m) thick near Collins Creek, west of the Rabbit Lake pit.

Post-Athabasca (?) mafic dykes are known in the area from at least three localities: south of Rabbit Lake, the B-Zone area, and on Harrison Peninsula.

STRUCTURE

Two major regional deformational events are recognized in the Rabbit Lake — Collins Bay area (Sibbald, 1983). The earlier phase of folding developed a prominent foliation (both in the basement and in Wollaston Group rocks) which is generally parallel to the original layering in the sediments. Second event folds are steeply inclined to upright, close to tight structures plunging gently to the northeast or southwest along northeasterly trending fold axes. This latter deformational event defines the strongly linear character of the Wollaston Domain. An example of this fold style is well exposed in the area south and southeast of the Rabbit Lake pit (Fig. 3). Folding of this character also appears to be developed on Harrison Peninsula and in the Collins Bay — Seal Lake area. The A-, B-, and D-Zone deposits, as well as the Eagle Point deposits, occur on the southeast limb of an overturned, tight to close anticline with a one-half wavelength of about four to five kilometres. Archean granitoid rocks in the core of the anticline exhibit a high magnetic relief, and the conductive lower Aphebian graphitic rocks define closure of this anticline to the northeast.

Two additional minor fold events were identified by Hoeve and Sibbald (1978) in the Rabbit Lake pit.

Two important fault directions are present in the map area: northeasterly and northerly.

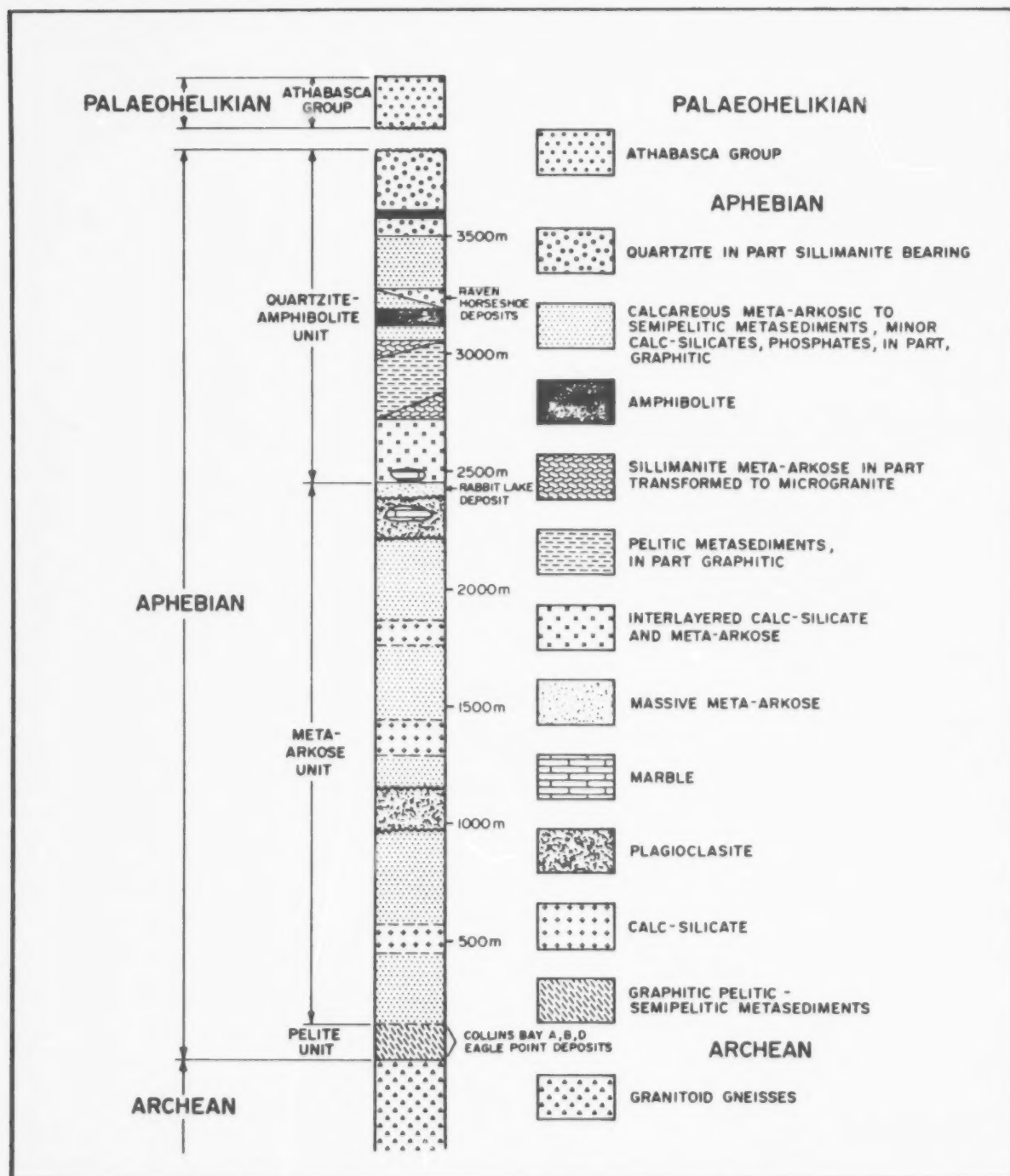


Figure 2. Schematic stratigraphic section of Wollaston Domain rocks in the Rabbit Lake — Collins Bay area.

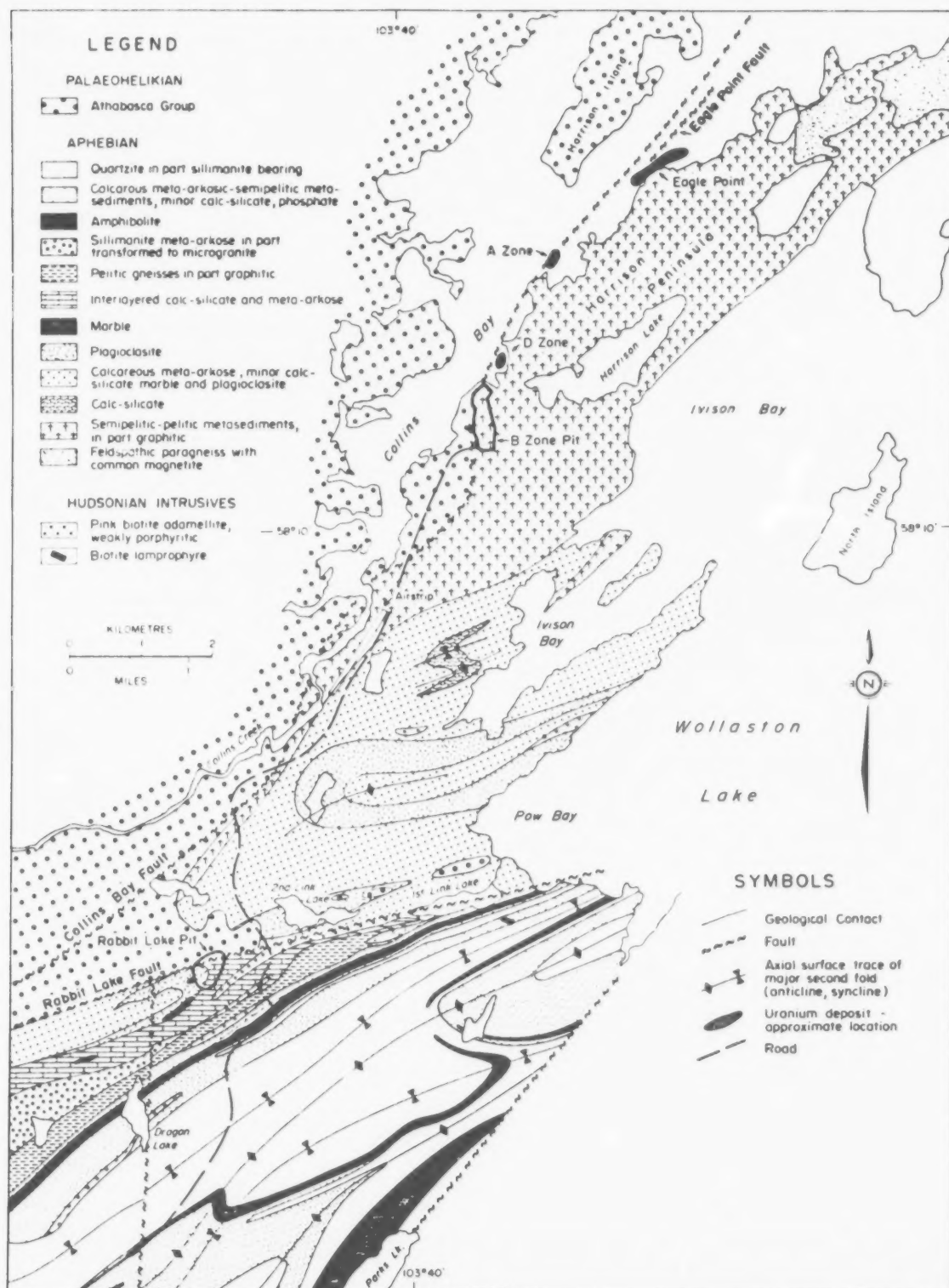


Figure 3. Geological map of the Rabbit Lake - Collins Bay area. Modified after Sibbald (1983).

The Rabbit Lake and Collins Bay Faults are northeasterly trending reverse faults of post-Athabasca and, possibly, pre-Athabasca age. They tend to be localized within graphitic horizons, wherein numerous planes of slippage are typically developed, and generally exhibit breccia-, shear-, and crackle-zones which are from 50 feet (15 m) to 300 feet (90 m) or more wide. Apparent vertical offset along these faults is in the order of about 300 feet (90 m); dips range from 30° to 60° southeasterly.

Northerly striking, subvertical, normal and/or wrench faults exhibit both pre-Athabasca and, probably, post-Athabasca movement. They tend to occur in locally alternating, sinistrally and dextrally displaced sets. Horizontal displacements along these faults are typically hundreds, and occasionally thousands, of feet.

METAMORPHISM

Upper-amphibolite-grade mineral assemblages typify most the Wollaston Domain. Coarse-grained to pegmatitic felsic segregations commonly occur within most lithologies, representing anatectic differentiates derived from the surrounding lithologies.

URANIUM DEPOSITS

Uranium deposits in the Rabbit Lake — Collins Bay area include the Rabbit Lake Mine (now exhausted), the Collins Bay A-, B-, and D-Zones, and Eagle Point.

The Rabbit Lake deposit has been discussed by Knipping (1974), Hoeve and Sibbald (1978), and most recently by Heine (1986). The A- and B-Zones have been discussed by Jones (1980). Some aspects of the Eagle Point deposits have previously been discussed by Sopuck et al (1983).

EXPLORATION HISTORY

The discovery in 1968 of the Rabbit Lake deposit in the Wollaston Lake area by Gulf Minerals Canada Ltd. (GMCL) established the potential of the Athabasca Basin as a host for uranium deposits. In the Collins Bay — Rabbit Lake area, this was followed by the subsequent discoveries of the Collins Bay A-Zone in 1971, the B-Zone in 1977, and the D-Zone in 1979 (Fig. 3).

The Eagle Point deposits were discovered by Gulf in 1980 through systematic exploration of electromagnetic conductors associated with the Collins Bay Fault in a northeasterly direction along strike from the A-Zone (Fig. 4). These conductors were first identified by a 1975 airborne Tridem survey and later by an INPUT survey flown in 1979.

In 1978, ground EM surveys were undertaken in the Eagle Point area to locate the airborne conductors.

Diamond drilling began to test these conductors in 1978, and the discovery holes for both Eagle North and Eagle South were drilled in February, 1980. The discovery hole was number 38 on Eagle North. At Eagle South, significant uranium in bedrock was located by a reverse circulation drilling program (hole number 28) that was following up uranium-in-basal-till anomalies located by this method in 1979.

Additional ground EM and magnetic surveys were undertaken in 1981 to define conductors and structures in more detail.

Drilling continued each year until 1982. After the completion of drilling in 1981, the mineralization at Eagle North was recognized to occur in three main zones (Fig. 5). At Eagle South, drilling had failed to define any significant mineralized zones comparable in grade or thickness with those at Eagle North.

In 1985, a joint-venture decision was taken to continue to drill the main zone (the 02 Zone) at Eagle North at 50-foot (15.2 m) grid centres, and to define the limits of mineralization along strike and down-dip and -plunge at the same drill-hole spacing. At Eagle South, drilling resumed at 100-foot (30.5 m) grid centres to test along strike and down dip. Drill hole 144 at Eagle South intersected the first concentration of uranium (3.75 per cent U₃O₈ over 99 feet [30.2 m]) which resembled the grades and thickness found at Eagle North.

In 1986, drilling further tested two zones (the 02 and 03 Zones) at Eagle North and the largest zone (144 Zone) at Eagle South at 50-foot (15.2 m) centres, and tested the Eagle South mineralization along strike and down dip at 100-foot (30.5 m) centres.

To date, drilling at Eagle South totals 217,364 feet (66,252.5 m) in 284 holes, and at Eagle North, 155,052 feet (47,260 m) in 245 holes, for a total of 372,416 feet (113,512.5 m) in 529 holes (Table 1).

Table 1. Eagle Point — diamond drilling history.

Year	Eagle South			Eagle North			Total		
	Holes	Total footage	Cumulative footage	Holes	Total footage	Cumulative footage	Holes	Total footage	Cumulative footage
1978	-	-	-	14	3,111	3,111	14	3,111	3,111
1979	-	-	-	12	2,468	5,579	12	2,468	5,579
1980	38	23,426	23,426	71	34,791	40,370	109	58,217	63,796
1981	86	40,902	64,328	85	55,584	95,954	171	96,486	160,282
1982	-	-	-	26	11,844	107,798	26	11,844	172,126
1983	-	-	-	-	-	-	-	-	-
1984	-	-	-	-	-	-	-	-	-
1985	56	60,194	124,522	14	15,827	123,625	70	76,021	248,147
1986	104	92,842	217,364	23	31,427	155,052	127	124,269	372,416
	284	217,364		245	155,052		529	372,416	

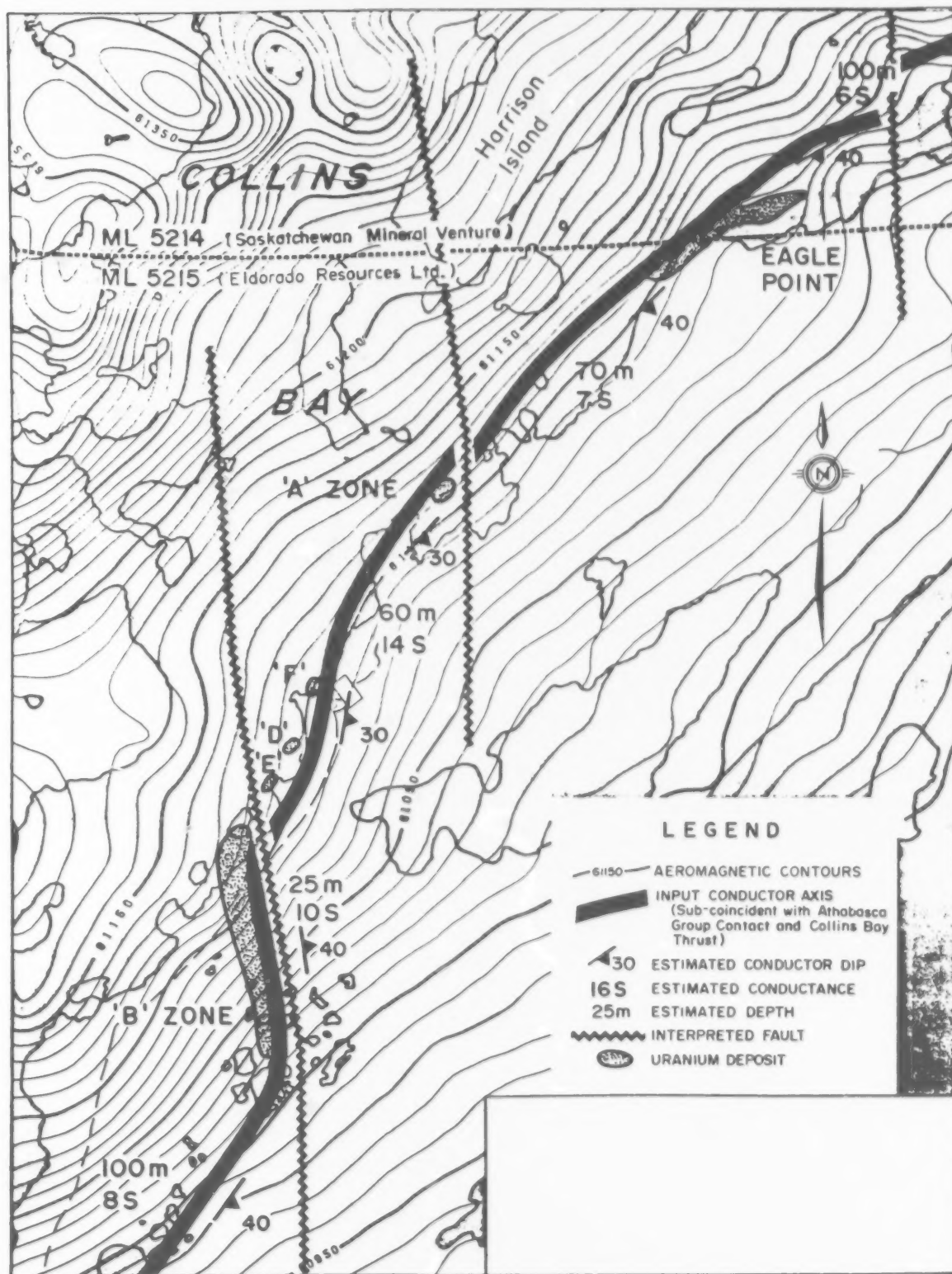


Figure 4. Geophysical response map of the Collins Bay B-Zone — Eagle Point area; scale approximately 1 : 28,500.

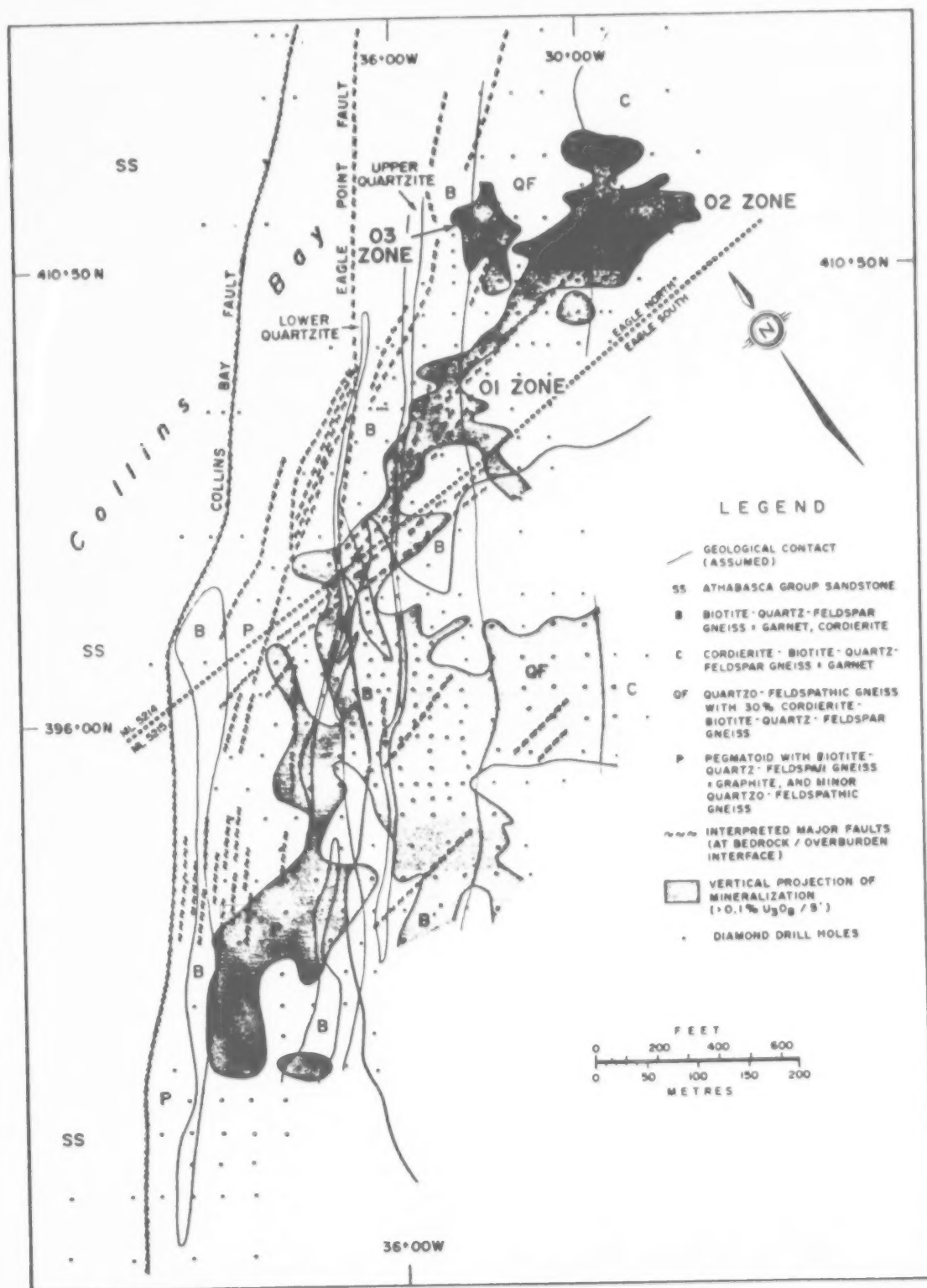


Figure 5. Geological map of the Eagle Point area.

Three main zones of uranium mineralization have been identified at Eagle North (the 01, 02 and 03 Zones) and two large and several small zones at Eagle South. The 02 and 03 Zones at Eagle North and about 50 per cent of the two largest zones at Eagle South have been defined by drilling at 50-foot (15.2 m) centres. Further definition and close-off surface drilling is required. However, because of the nature of the deposits, future exploration drilling of the down-dip extension of the mineralization will be more efficiently carried out from underground.

DEPOSIT GEOLOGY

The deposit area is underlain by Aphebian paragneisses of the Wollaston Group and related Hudsonian pegmatoids, and by Lower Aphebian or possibly Archean granitoid gneiss. Fluvial sandstone and conglomerate of the Manitou Falls Formation of the Helikian Athabasca Group occur immediately to the west of the Collins Bay Fault, and unconformably overlie the older gneisses. Two major reverse faults transect the deposit area and are more-or-less conformable with the stratigraphy. The upper fault, termed the Eagle Point Fault, is well developed at Eagle North and appears to dissipate in the Eagle South deposit area. The lower fault, termed the Collins Bay Fault, is a major regional feature, occurring near the base of the Aphebian section and very near the top of the Archean (?) granitoid basement. Both faults are discussed in detail elsewhere.

The surface projection of the geology and structure relative to the drill-hole collar locations is presented in Figure 5.

A stratigraphic column for the Eagle Point deposits is given in Figure 6.

A typical section illustrating the main geological elements of each of the Eagle South and Eagle North deposits is presented as Figures 7 and 8 respectively; these are sections 396+00N and 410+50N.

QUATERNARY

The Eagle North deposit is situated beneath Wollaston Lake near the east shore of Collins Bay. Water depths range up to approximately 40 feet (12 m) at the extreme northern and western limits of the deposit area. The Eagle South deposit straddles the shoreline of Collins Bay, extending offshore to where the water is about 25 feet (8 m) deep. Bedrock is covered by an average of 25 to 30 feet (8 to 9 m) of bouldery glacial till, with minor lacustrine sediments.

HELIKIAN

The Helikian Athabasca Group is confined to the west side of the Eagle Point drilling area, on the footwall side of the Collins Bay Fault. It consists of sandstones and conglomerates of the Manitou Falls Formation.

The Athabasca Group directly overlies the Archean (?) granitoid.

HUDSONIAN PEGMATOID

Potassium feldspar, plagioclase, and quartz are the major constituents of this rock type, the dominant features of which are its coarse texture and felsic composition. Myrmekitic intergrowths of quartz and feldspar are common. Variable but minor quantities of biotite, garnet, sillimanite, tourmaline, and cordierite are frequently present. This lithology represents an anatectic segregation rather than a true magmatic

pegmatite. Its mineralogical composition, therefore, depends to some extent on the rock type(s) immediately adjacent to it.

This unit occurs throughout the Aphebian sequence and, to a lesser extent, in the Archean (?) granitoid gneiss. It generally forms narrow discontinuous zones. However, thicker, more continuous zones occur near the base of the Aphebian section, close to the Collins Bay and Eagle Point Faults. This unit is estimated to make up 15 to 20 per cent of the Aphebian sequence in the deposit area.

APHEBIAN

A 1500-foot-thick (460 m) sequence of Aphebian rocks hosts the Eagle Point deposits. These rocks form a northeasterly striking (035°), southeasterly dipping (40-55°), lithologically variable metasedimentary sequence, which probably represents a shallow-marine, near-shore, and, in part, restricted depositional environment. Mudstones with some organic debris are thought to have been intercalated with fine-grained detrital rocks (arkose and minor quartzite). Minor iron-rich sedimentary rocks may have volcanic (basaltic) affinities. Calcium-rich mudstones indicate that evaporitic conditions may, at times, have prevailed locally.

This sequence (Fig. 6) was subsequently metamorphosed to the amphibolite facies.

Several rock types have been mapped in the area; they commonly grade into one another.

Biotite-quartz-feldspar gneiss contains abundant quartz and plagioclase, and variable amounts of biotite (in excess of 10 per cent, and generally close to 20 to 25 per cent). Other minerals present include potassium feldspar, garnet, cordierite, sillimanite, pyrite, and graphite, along with minor quantities of apatite, tourmaline, sphene and zircon.

Texturally, the gneiss is fine- to medium-grained, moderately to well foliated and, in most places, well banded. When fresh, it is medium to dark grey in colour.

Biotite-quartz-feldspar gneiss is the dominant rock type in the deposit area, and comprises 30 to 40 per cent of the Aphebian sequence (Fig. 6).

Cordierite-biotite-quartz-feldspar gneiss is similar in composition to the biotite-quartz-feldspar gneiss, but contains more than ten per cent cordierite as pinitized, blue-green, small- to medium-sized grains which often occur as augen near fault zones. This unit makes up from five to ten per cent of the stratigraphic sequence (Fig. 6).

Garnet-biotite-quartz-feldspar gneiss is also similar in composition to the biotite-quartz-feldspar gneiss, but has more than five per cent garnet, which forms idioblastic to subidioblastic, small to large porphyroblasts. In places, garnet is massive over small intervals, a feature which, when well developed, makes this rock unit difficult to distinguish from amphibolite. Garnet is generally pink to mauve when fresh, but is usually altered to chlorite. It has been identified as pyrope.

This unit comprises approximately five per cent of the Aphebian stratigraphy (Fig. 6).

Garnet-cordierite-biotite-quartz-feldspar gneiss compositionally resembles biotite-quartz-feldspar gneiss but

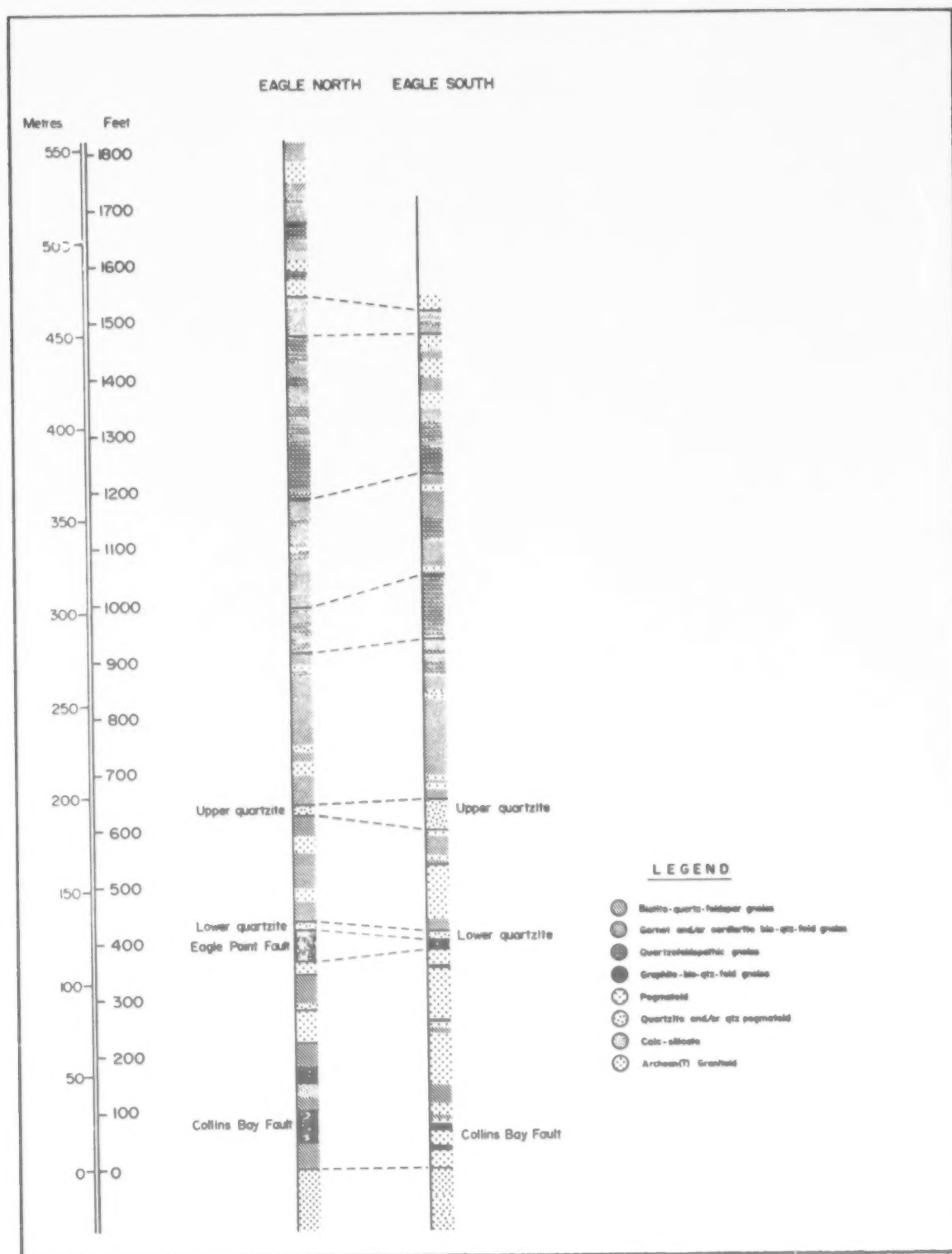


Figure 6. Schematic stratigraphic vertical section of Archean (?) and Aphebian rocks in the Eagle Point area.

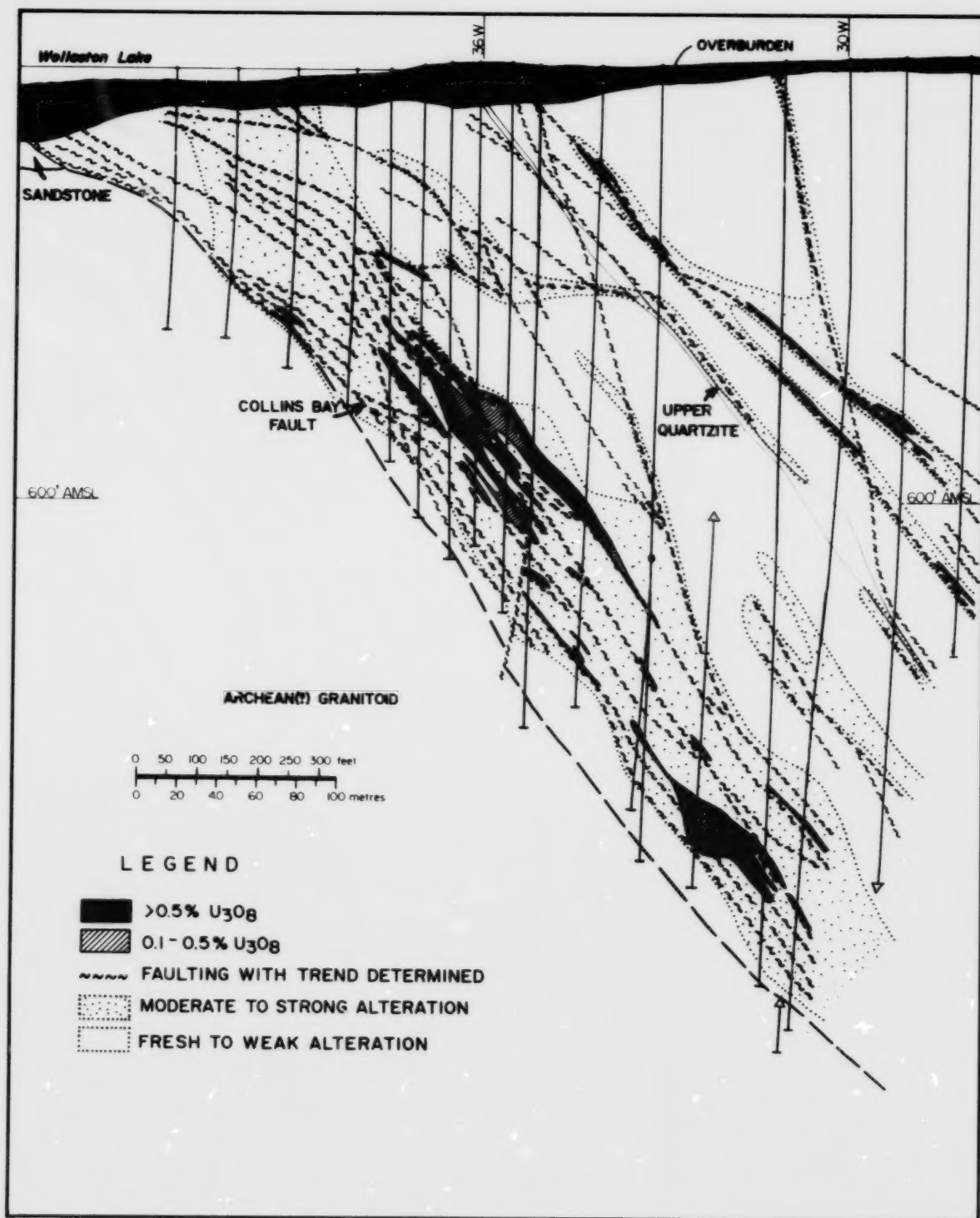


Figure 7. Cross-section (NW-SE) of the Eagle South deposit (section 396+00N).

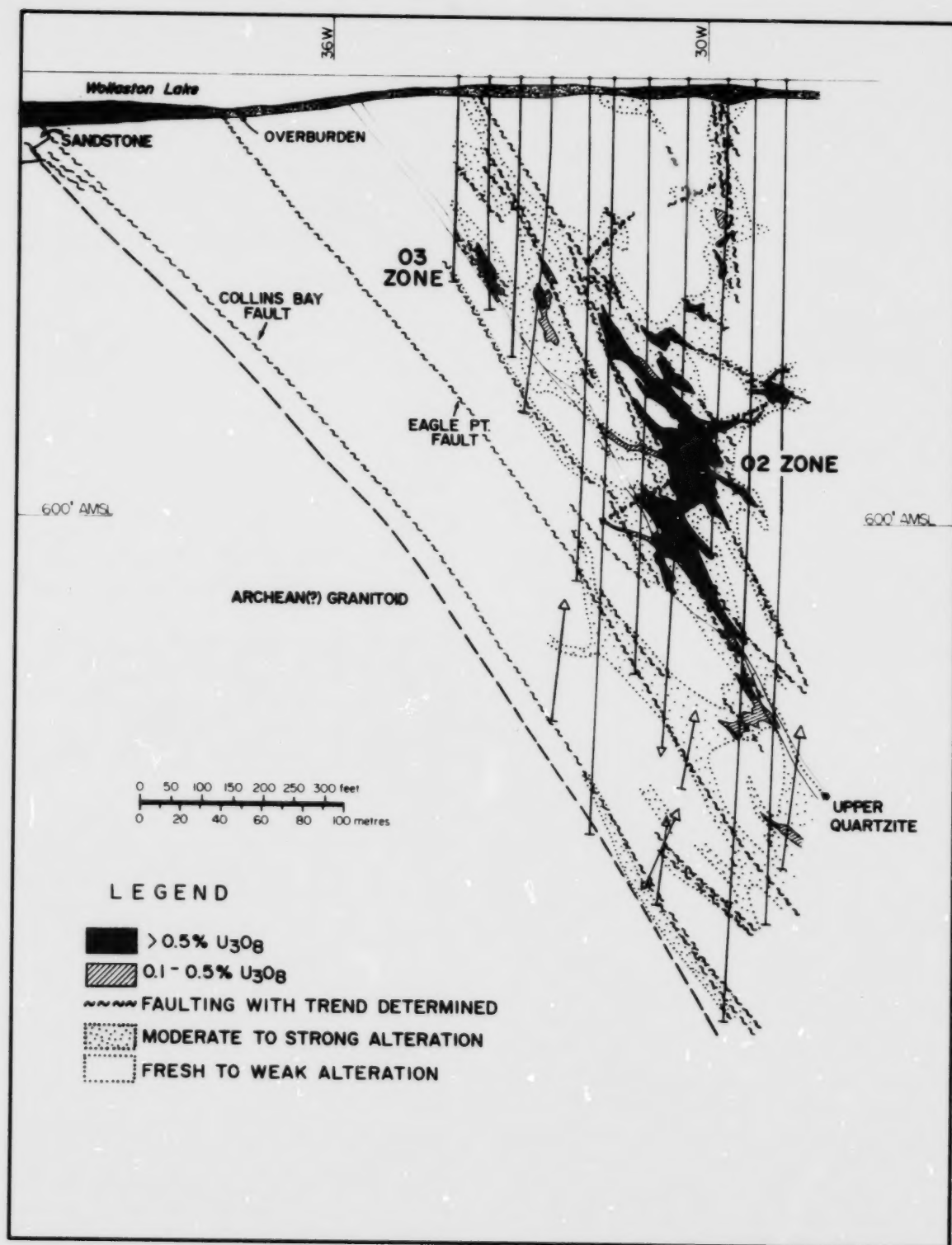


Figure 8. Cross-section (NW-SE) of the Eagle North deposit (section 410 + 50N).

contains more than five per cent garnet and ten per cent cordierite. When highly altered, it is indistinguishable from most other Aphebian paragneisses as both garnet and cordierite have broken down into chlorite, pinite and other product minerals.

Garnet-cordierite-biotite-quartz-feldspar gneiss comprises less than five per cent of the Aphebian stratigraphy (Fig. 6).

Graphite-biotite-quartz-feldspar gneiss contains in excess of five per cent graphite as grains along foliation planes, as disseminated flakes, and in massive form. From one to five per cent pyrite is typically present. One band of this rock type occurs near the base of the Aphebian sequence, where it is a locus for major faulting. In the deposit area, both the Collins Bay and the Eagle Point reverse faults are developed almost entirely within this lithology. Graphite has been mobilized along the faults, and forms concentrations which make up to 50 per cent of the rock.

This unit comprises five per cent or less of the stratigraphic sequence, but is important in relation to the mineralization process in that it provides a locus for faulting.

Quartz-feldspar gneiss dominates the upper portion of the Aphebian sequence. It contains mostly plagioclase, 10 to 25 per cent quartz and less than 10 per cent biotite. Accessory garnet, sillimanite, potassium feldspar, graphite, apatite, tourmaline, zircon and pyrite may be present. Where sillimanite forms more than five per cent of the rock, a separate unit (see below) has been distinguished. The quartz-feldspar gneiss is weakly foliated to massive and medium- to coarse-grained. In places, it looks like granite. It contains numerous anatectic pegmatoids similar in composition to the host rock. Its poorly foliated to massive appearance is primarily due to the paucity of biotite.

This rock type comprises 15 to 20 per cent of the Aphebian sequence in the deposit area (Fig. 6).

Sillimanite-quartz-feldspar gneiss is mineralogically similar to the quartz-feldspar gneiss, but contains more than five per cent sillimanite and minor amounts of garnet. The sillimanite occurs as aggregates of fibrous crystals, which, together with the biotite, give the rock a weakly foliated texture. The outer margins of the sillimanite are typically hematite-stained, imparting a pink or red colour to the rock.

Quartzite contains more than 75 per cent quartz, about 25 per cent plagioclase and accessory sillimanite, garnet, biotite, and sphene. Massive, coarse-grained to pegmatitic quartzite and foliated medium- to coarse-grained quartzite occur within the sequence, often together, and are interbanded with impure quartzite containing more than 25 per cent feldspar. Some of these rocks are not true quartzites but are probably anatectic derivatives of quartz-rich metasediments.

Quartzite units are common throughout the stratigraphic column, and range in thickness from 0.5 (15 cm) to 60 feet (18 m) or more. They usually form discontinuous lenses, but two fairly continuous units have been recognized which, where present, serve as excellent marker horizons (termed the upper and lower quartzites at Eagle Point).

The lower quartzite is generally narrower and less continuous than the upper unit, and occurs a few feet above the Eagle Point Fault. The main marker horizon, the upper quartzite, is

situated approximately 125 feet (40 m) above the lower unit, and is up to 60 feet (18 m) thick. A parallel and, in places, mineralized fault system has been recognized immediately above this unit.

The quartzites are volumetrically insignificant, comprising only one to two per cent of the Aphebian sequence.

Calc-silicate rocks also form only a small portion of the Aphebian metasediments. They occur as one- to fifteen-foot-thick (0.3 to 4.6 m) layers which, although noted throughout the Aphebian sequence, are generally associated with quartzites and mafic gneisses. The layers are discontinuous and rarely traceable for farther than 100 feet (30 m) along strike. They probably represent calcareous mudstones.

Calc-silicates contain clinopyroxene (diopside), amphibole and garnet as major constituents, and quartz, calcite and plagioclase as subordinate minerals.

Marble is rare, generally occurring as narrow bands within calc-silicate rock. It is made up mostly of dolomite and/or calcite.

Amphibolite comprises a minor part of the stratigraphic sequence in the Eagle Point area, and consists of garnet, diopside, amphibole, cordierite and biotite with minor amounts of plagioclase. The unit is quite continuous from hole to hole, and may contain sections carrying up to 50 per cent massive garnet over several feet. Generally, this unit is weakly to moderately magnetic.

LOWER APHEBIAN (ARCHEAN?) GRANITOID

This unit is weakly foliated, medium- to coarse-grained, crystalline, and equigranular. It underlies the Aphebian gneissic sequence in the Eagle Point area. Composed of quartz, potassium feldspar, plagioclase, five to ten per cent biotite, and minor garnet and sillimanite, it is distinguishable from the Aphebian biotite-quartz-feldspar gneiss by the absence of coarse banding.

This granitoid unit probably represents basement to the Wollaston Group. At Eagle Point, Pb/Pb ratios suggest that the age of the granitoid is at least 2000 to 2100 Ma and that the U/Pb system in the granitoid has been extensively modified at about 1305 Ma.

STRUCTURAL GEOLOGY

GENERAL

Since structural interpretation of the Eagle Point area is an ongoing process, this account is subject to future refinement.

The Eagle Point deposits are hosted by a sequence of Aphebian paragneisses which overlies an older Archean (?) granitoid basement. The rocks form a homocline, the axial plane of which strikes northeasterly and dips at about 45° to the southeast. Reverse faulting within the Aphebian metasediments is a dominant structural feature of the deposits, and the mineralization is controlled either by reverse faults, or by other attendant faults and breccia zones. Fault orientation has been influenced by factors such as inhomogeneities in the stratigraphy of the metamorphic rocks, undulations in the surface of the basement granitoid, and — possibly — by folds in the metasediments; these factors thus indirectly influence the distribution of the mineralized zones.

FAULTING

Introduction. The localization of uranium mineralization at Eagle Point is entirely controlled by faults and their attendant breccias. The morphology of these faults has been influenced by the layered nature and marked contrasts in competency of the paragneiss sequence, by the configuration of the Archean (?) - Aphebian unconformity, and probably by folds within the gneisses. Because the major reverse faults tend to follow less competent stratigraphic units (usually graphitic paragneiss), parts of the mineralized zones controlled by these faults appear to be "stratabound". However, significant portions of the mineralized zones also occur in structures which clearly crosscut the stratigraphy, particularly at Eagle North.

Mineralization is present in at least three sets of faulted and brecciated structures:

- 1) reverse faults,
- 2) steeply dipping faults and breccias, and
- 3) north-dipping faults.

Reverse faults. Two principal zones of reverse faulting, the Collins Bay Fault (CBF) and the Eagle Point Fault (EPF), are present. At Eagle South, the EPF is more poorly defined than at Eagle North.

The EPF and CBF typically consist of zones of brittle deformation, with intervals of graphitic breccia (both healed and unhealed), slips, shears and gouge, localized within graphitic paragneiss and pegmatoid units. Strong evidence exists for multiple periods of movement with, for example, zones of unconsolidated breccia and gouge in sharp contact with healed (silicified) breccia. The local presence of graphitic breccias within otherwise non-graphitic pegmatoid wall rocks indicates that graphite has been introduced and mobilized along the faults.

The average width of the Eagle Point and Collins Bay Faults is approximately 30 to 60 feet (9 to 18 m) at Eagle North. The stratigraphic separation between the two reverse faults is about 170 to 190 feet (52 to 58 m) [270 to 300 feet (82 to 91 m) vertically]. Their strikes about 035°, consistently coincide with the strike of the enclosing paragneisses; dips range from 40° to 55° southeast. Both faults tend to flatten in an up-dip direction. This curvature of the fault zones may reflect warping of the enclosing gneisses or irregularities in the surface of the granitoid.

Reverse movement on the Collins Bay Fault has pushed the Aphebian gneisses over basal units of the Athabasca Group and the sub-Athabasca paleoweathered zone. As the unconformity in the hanging wall has been eroded away, the amount of vertical movement on the Collins Bay Fault at Eagle Point is unknown. However, in the Rabbit Lake and Highway 905A areas, reverse vertical displacement is about 300 feet (91 m). At the B-Zone Mine, located along the CBF, movement is also known to be reverse.

In the Eagle North deposit, the EPF is observed in drill core to form a much wider zone than the CBF. It shows more evidence of "late" movement, such as gouge, clay, and breccia. This suggests that the EPF took up more of the late stress than did the CBF and possibly explains the lack of significant uranium mineralization below the EPF (due to the absence of suitable dilatencies) at Eagle North.

In the Eagle South deposit, the CBF is observed in drill core to consist of a broad zone of anastomosing faults and breccias

with a true thickness of about 180 to 220 feet (55 to 67 m). It occurs in the lower graphitic horizon and in an overlying pegmatoid. The graphitic unit which hosts the EPF at Eagle North is not strongly faulted at Eagle South. The faulting associated with this horizon at Eagle South is minor, discontinuous, and generally unmineralized.

Minor foliation-parallel faults have been observed at both deposits, almost exclusively in the zone above the EPF. They are probably genetically related to the major reverse faults. Structural interpretation in this area, which appears also to contain minor crosscutting faults, remains somewhat ambiguous.

Steeply dipping faults and breccias. Steeply dipping breccia zones host a significant proportion of the mineralization at Eagle North, for example in the 01 and 02 Zones which are probably located on different parts of the same structure. They strike at about 080°, with dips ranging from, most commonly, 80° north to 80° south. Subvertical faults and fractures are commonly observed in core from the vicinity of mineralization, and their presence is deducible from the distribution of mineralization in drill sections. They are restricted to structurally high portions of the Wollaston Group, and do not extend much below the level of the Eagle Point Fault. They do not appear to offset or otherwise disrupt the EPF.

North-dipping faults. A number of north-dipping faults seem to be present. Most of the ambiguity remaining in the structural interpretation of the Eagle Point area concerns these structures. The intersection of one such fault in adjacent drill holes could be alternatively explained as being due to a series of sub-parallel reverse faults. The principal evidence for their existence is the apparent northerly dip of some of the mineralized veins, and the association of this mineralization with faults.

Relationship of mineralization to faulting. The three fault sets mentioned above are the only ones currently recognized to contain mineralization. In any given zone, mineralization is typically present in structures of more than one orientation. Faults that cut across the stratigraphy provide conduits to link stratabound veins at different stratigraphic levels. Hydrothermal solutions moving through crosscutting structures were offered egress to stratabound reverse fault zones, or to stratigraphic horizons with favourable permeability. A ladder-like pattern of mineralization thus appears to have developed, particularly at Eagle North.

Other fracture systems and orientations. Structural trends other than those described above are less well documented at this time, in part because interpretation of much of the Eagle South data is still in progress. Other possible trends include:

- a) **Northwesterly striking faulting:** whereas the major fault trends are well documented, most healed fractures (forming veinlets of quartz $\pm$ calcite $\pm$ pyrite $\pm$ pitchblende, and considered "minor" in nature with respect to uranium mineralization) have not yet been systematically analysed as to location and orientation with respect to core angles and foliations. Partial documentation of the attitude of these veinlets (fewer than 50 determinations) indicates that more than 90 per cent of them strike approximately normal to the foliation and have a dip of greater than 70°, both northeasterly and southwesterly.

b) **Northerly striking faults:** the existence of such faults on a regional scale is well established. They are probably subvertically dipping wrench faults and are known from work by various groups in many areas both to predate and postdate the deposition of the Athabasca Group. They probably date from at least the late Hudsonian, and may possibly reflect faulting of crustal dimension from much earlier time. Faulting of this set has been suggested to cut across the Eagle North deposit area, and to have dispersed the uranium mineralization both upwards and downwards in the stratigraphy. These northerly striking faults have been interpreted from magnetic and VLF-EM data, but have not yet been confirmed in drill core in the deposit area.

FOLDING

Regional-scale folding is interpreted to occur on Harrison Peninsula and in the Collins Bay — Seal Lake area.

Smaller scale folding deforms Aphebian rocks in the deposit area, and, in some cases, may indirectly influence the location of mineralization.

Hinges of minor folds are commonly seen in drill core, and the orientation of foliations in any given section of core is found to change from place to place. These two observations indicate that paragneisses at Eagle Point have been folded, perhaps extensively.

ALTERATION

Petrographic and analytical studies of host-rock alteration at Eagle Point have been done by GMCL, by Sopuck et al (1983), and — most recently — by Eldorado. The interpretation of the alteration pattern presented here is based on 'macroscopic' observations made during routine core logging supplemented by limited analytical work. Further detailed work is required to document adequately the chemistry, mineralogy and other features related to alteration.

At present, most Aphebian rocks intersected in drilling at Eagle Point are recognizably altered to some degree. In general, the freshest rocks in the deposit area occur at the greatest distances from mineralization. Also, the degree and extent of alteration tends to decrease with depth below the main mineralized zones, both vertically and down the stratigraphic dip.

For the most part, all silicates except quartz are replaced to varying degrees by hydrated phyllosilicates. Amphibole and cordierite are the most readily altered minerals. Garnet, plagioclase, biotite and potassium feldspar are more stable.

Alteration products have been identified using X-ray-diffraction and electron-microprobe methods. Amphibole and garnet appear to be replaced mainly by chlorite; cordierite by illite and chlorite; biotite by clay minerals, chlorite, and Fe-hydroxide, with leucocratic Fe-Ti oxides along cleavages; and plagioclase by illite, other clay minerals and carbonate.

Carbonate, probably calcite, and illite commonly replace plagioclase. Carbonate has also been seen replacing the phyllosilicate matrix of completely altered gneiss, and is associated closely with pitchblende.

The phyllosilicate mineralogy and the spatial distribution of these minerals have not yet been systematically studied, but work to date (Fischer, 1982) suggests that magnesian chlorite (Mg/Fe ratio from 7 to 20) predominates down to depths of about 250 feet (ca. 75m) below bedrock surface, and that magnesium-iron chlorite (Mg/Fe ratio of about one) predominates below about 250 feet (ca. 75 m).

At least four types of alteration have been postulated and/or recognized:

- 1) paleoweathering of pre-Athabasca age;
- 2) retrograde alteration associated with faulting of both pre- and post-Athabasca age;
- 3) possible magnesium metasomatism caused by diagenetic-hydrothermal fluids circulating through the Athabasca Basin during and after deposition of the Athabasca Group rocks; and
- 4) alteration spatially related to mineralization, of which at least three generations have been identified.

Typically, however, the chemical inhomogeneity of the metasedimentary units tends to mask all but the most prominent features of the lithogeochemical character and pattern of the several alteration types.

1. Lateritic paleoweathering — typified by its characteristic red, oxidized zone overlying a reduced, green zone — occurs beneath the Athabasca Group throughout the Athabasca Basin. It is present in the deposit area in the footwall of the Collins Bay Fault, where Archean(?) granitoid rocks occur directly below the Athabasca cover.

Hematitic alteration also occurs in the hanging wall of the Collins Bay Fault at the bedrock surface in scattered pockets and areas, possibly as remnants of the oxidized paleoweathering profile. However, the distribution of these areas and the nature of the alteration have not yet been well studied.

2. Retrograde alteration genetically related to late faulting and typified generally by variable degrees of chloritization of mafic minerals and clay alteration of feldspar has not been conclusively documented as a uniquely separate event. Observation and limited analytical work to date have indicated that the chloritization of mafic minerals, particularly cordierite, and the illitization and sericitization of plagioclase are at least incipiently developed throughout the deposit area in the hanging wall of the Collins Bay Fault. These effects are accompanied by soda (Na₂O) depletion (Sopuck et al, 1983). Visually, these altered rocks resemble "green zone" rocks in the typical paleoweathering profile. Mineralogically, they appear to be indistinguishable from green zone rocks (Sopuck et al, 1983). At Rabbit Lake, Hoeve and Sibbald (1978) recognized an early alteration event typified by dark green chloritization in rocks hosting the orebody, and proposed (p. 1461) that this chloritization "...may have been derived from the late Hudsonian retrogression."

Thus, the widespread incipient to weakly developed chloritization may be of two different ages — late Hudsonian or Helikian — or may more likely be of both ages, with the Helikian event overprinting the late Hudsonian.

3. Fischer (1982) speculated that a muscovite/illite - chlorite assemblage (with this chlorite having a high Mg/Fe

ratio), which is widely distributed at shallow depths in both barren and mineralized sections, may indicate **Mg-metasomatism** caused by solutions that prevailed in the Athabasca Basin after the deposition of the Athabasca Group. He interpreted this event to be separate from, and later than, the first mineralization event.

4. Alteration spatially related to mineralization is characterized by bleaching of the mafic minerals, chloritization and illitization of feldspar, and hematization. It is generally moderately to strongly developed. All silicates except quartz, which is usually preserved except in completely altered "clay rock," are replaced to varying degrees by hydrated phyllosilicates. In the highest grade parts of the mineralized zones, illite is the dominant phyllosilicate with little to no chlorite; in lower grade material, chlorite and illite are present in about equal proportions.

Paragenetically, hematization directly associated with mineralization clearly forms one of the latest alteration events.

Silicification is spatially related to mineralization to only a minor extent. Healed breccia zones well removed from mineralization are typically silicified. Silicification occurs within, and very close to, the quartzitic metasedimentary units, and invades adjacent units as quartz veins and silicified zones of limited extent. Silica $\pm$ carbonate $\pm$ pyrite veinlets are common throughout the deposit area, but their distribution and frequency have not yet been systematically documented.

At Key Lake, Sopuck et al (1983) recognized that, in the basement funnel zone of alteration below the Deilmann deposit, the green alteration is texturally, mineralogically, and chemically similar to alteration found in the lower green layer of the regolith in regional holes. They noted, however, that intense silicification, tourmalinization (dravite), and chloritization are characteristic of the centre portion of the hydrothermal root zone. At Eagle Point, **boron enrichment** appears to be associated with, and limited to, the bleached zones within a few tens of feet from mineralization and along the graphitic conductive zones (Sopuck et al, 1983). Silicification is only a minor feature related to mineralization.

Limited work to date suggests that uranium in the alteration haloes around the mineralized lenses is enriched by a factor of up to ten.

At Eagle North, alteration associated with mineralization is restricted to relatively narrow zones around and along both mineralized and unmineralized faults and fracture systems. Here, within a few tens of feet of mineralization, the host rock is fresh-looking or is only weakly altered. At Eagle South, the alteration is more extensive and pervasive because of the apparent greater density of faulting. In general, however, mineralization-associated alteration, which is of restricted distribution compared to the clay alteration in the Athabasca Group around the typical unconformity-type deposits, does not significantly enlarge the exploration target.

MINERALIZATION

Uranium mineralization at Eagle Point occurs in lenses, pods, and veins which are both concordant and discordant to the metamorphic stratigraphy, and which are distributed through a stratigraphic thickness of at least 1000 feet (305 m).

The mineralization at Eagle Point is structurally controlled, occurring as fault- or fracture-fillings and as impregnations into altered paragneisses and pegmatoid rocks.

The total strike length of mineralized rock is about 3300 feet (1000 m) (Fig. 5). The main mineralized zones generally have a total vertical width of approximately 300 feet (90 m), in places ranging up to about 800 feet (245 m). Mineralization extends to a vertical depth of at least 1200 feet (365 m) below the present bedrock surface.

At Eagle South, five distinct zones have so far been identified. The two largest of these zones occur as concordant, tabular lenses which dip about 45° towards the southeast; they are subparallel to, and lie immediately above, the Collins Bay Fault (Fig. 7). In section, these zones are about 300 to 400 feet (90 to 100 m) long and 60 to 120 feet (18 to 36 m) thick. They occur entirely within sheared and faulted pegmatoid.

At Eagle North, most of the mineralization occurs in three distinct zones, the largest of which is the 02 Zone (Fig. 8). In plan, the 01 Zone is about 420 feet (128 m) by 100 feet (30 m), the 02 Zone 700 by 250 feet (213 by 76 m), and the 03 Zone about 200 by 100 feet (60 by 30 m). In cross-section, these three zones are very ragged, with a depth-to-width ratio of approximately 1:1 to 2:1. These zones are, in part, elongated subparallel to the foliation in cross-section, but clearly transect several lithological units. The long axes of the 01 and 02 Zones plunge at about 40° towards 080°. The lensoid 03 Zone has no obvious strike or dip direction. Other, less significant zones occur in northeasterly striking, northwesterly dipping faults.

At Eagle South, the majority of the mineralized lenses are confined to within about 500 feet (150 m) of the Archean (?) granitoid surface (measured perpendicular to this surface). Here, the EPF and CBF appear to converge into an anastomosing series of breccias and fault zones. The mineralization occurs within this zone and has not been found below the CBF.

At Eagle North, uranium mineralization occurs mainly above the Eagle Point Fault, with only weak mineralization in the fault itself. This mineralized section begins about 200 feet (60 m) above the Archean (?) granitoid surface (measured perpendicular to this surface).

URANIUM MINERALIZATION

The Eagle Point deposits are mineralogically simple, consisting of several generations of uraninite and pitchblende. All other metals (particularly impurities such as As, Ni, and Mo) are present in only trace amounts (Table 2). This is one of the notable differences between the Eagle Point mineralization and that of other unconformity-type deposits such as Key Lake, Cigar Lake, and the Collins Bay B-Zone, where Ni and As are present as major constituents.

Several forms of uranium mineralization have been identified at Eagle Point:

- 1) Generation I uraninite**, highly reflective in polished section and consisting of well formed cubes, represents the oldest generation of uranium mineralization preserved in the deposit; the cubes commonly show incipient cataclastic deformation (Fig. 9);
- 2) Generation II uraninite** is formed by oxidation of Generation I uraninite and is pseudomorphous after

Table 2. Uranium and minor element concentration of a composite sample from the 02 Zone, Eagle North (all units ppm unless otherwise noted).

Ag (oz/t)	0.16
As	60
Au (oz/t)	0.002
Bi	60
Ca	3300
Cd	less than 10
Co	60
(CO ₂) ⁻⁻⁻	4400
Cr	120
Cu	370
Fe (total) (per cent)	1.22
Mn	750
Mo	620
Ni	90
P	200
Pb	1570
Pt (oz/t)	less than 0.001
Sb	less than 10
Se	less than 20
Sn	less than 10
Te	2.2
U (per cent)	1.865
V	400
Zn	less than 50
Zr	270

it (Fig. 10); Generation II crystal development was commonly followed by reaction of these crystals with pore fluids, resulting in their removal by dissolution and replacement by siliceous material;

- 3) **pitchblende occurring as veins** crosscuts both generations of uraninite, which it therefore postdates; it probably represents redeposition of UO₂ removed from Generation I and II uraninite (Fig. 11);
- 4) **pitchblende rimming and filling fractures in quartz grains** occurs in areas of porous rock; here, the quartz grains, being impermeable and generally non-reactive, acted as barriers to circulating mineralizing solutions which "welled up" against them to form rims and fill fractures (Fig. 12);
- 5) **pitchblende in biotite** commonly occurs as oriented inclusions along cleavage planes;
- 6) **boltwoodite** [K₂(UO₂)₂(SiO₃)₂(OH)₂·5H₂O] has been identified by X-ray diffraction; this secondary uranium mineral represents the youngest stage of uranium mineralization, and is common in rocks which contain altered biotite, suggesting that the potassium it contains was derived from the biotite; in many places, boltwoodite cements fractured areas; and
- 7) **coffinite** [U(SiO₃)_{1.5}(OH)_{0.5}] has been positively identified by X-ray diffraction in only one specimen, in which it occurs only in trace amounts.

Notably, boltwoodite and coffinite account for less than one per cent of the total uranium species. The major species are uraninite and pitchblende.

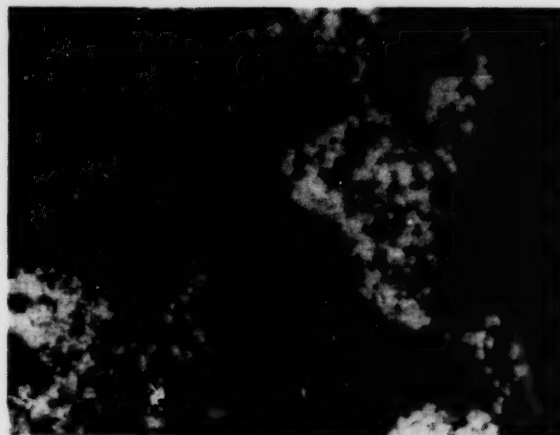


Figure 9. Generation I uraninite cubes; scale: 1 cm = 0.14 mm.

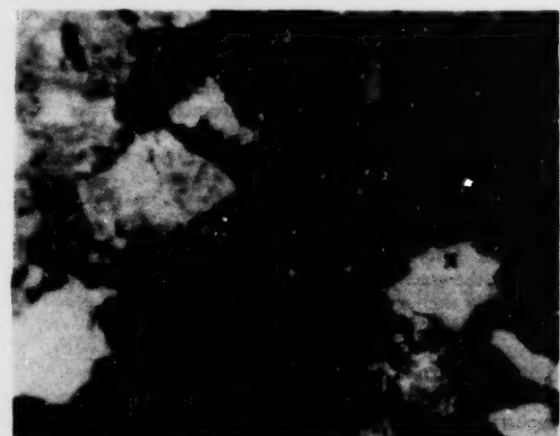


Figure 10. Generation I and II uraninite; cubes of Generation I uraninite (X) with high reflectivity are adjacent to cubes of Generation II uraninite with low reflectivity (Y); scale: 1 cm = 0.028 mm.

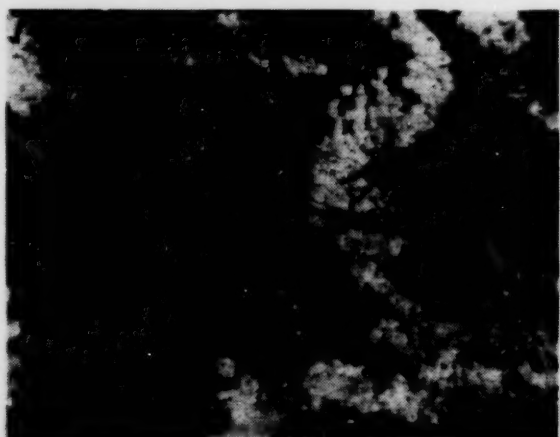


Figure 11. Generation I uraninite (X) cut by a vein of pitchblende (P); scale: 1 cm = 0.14 mm.



Figure 12. Altered paragneiss containing massive pitchblende (P) indurating an illite-rich matrix (I) and rimming quartz grains (Q); scale 1 cm = 0.14 mm.

BASE METAL SULPHIDES AND ARSENIDES

Base metal sulphides, mainly pyrite (FeS_2), galena (PbS), and chalcopyrite (CuFeS_2), are present only in trace amounts (Table 2), and generally constitute less than one per cent of the total mineralization.

Pyrite is the most abundant of these, and locally makes up to several per cent of the rock. At least two generations have been recognized. The older pre-dates Generation 1 uraninite, occurring in fresh biotite gneiss as roundish-to-subidioblastic, large grains which are part of the metamorphic fabric; it forms 0.05 to 2 per cent of the rock. The younger generation of pyrite occurs in narrow fractures with carbonate and/or quartz. Its age relative to uranium mineralization is uncertain, but, in part, postdates alteration associated with mineralization.

Galena occurs as:

- specks in uraninite and pitchblende formed by the reaction of radiogenic lead with sulphur;
- well shaped grains (cubes), in places associated with cubes of uraninite;
- oriented inclusions in cleavage planes of biotite;
- fracture fillings in barren rocks; and
- dendritic veinlets associated with pitchblende.

Massive segregations of galena, where present, exhibit a wide range of textural features. Locally significant remobilization of uranium oxide has possibly left behind less mobile galena.

Chalcopyrite is rare, is generally associated with high-grade mineralization as well shaped specks, and is present only in very small amounts. Rare globules of native copper occur within and adjacent to the uranium mineralization, as cubes replacing uraninite I, as veins in fractures, and along cleavage planes in biotite.

No arsenides have been detected.

CARBONACEOUS MATTER

Carbonaceous material with a characteristic odour is associated with higher grade mineralization. It generally occurs in very low concentrations as small sooty blebs and

buttons, thus resembling material from Cluff Lake described and studied by Landais and Dereppe (1985). These authors identified it as bitumen, containing 60 to 80 per cent carbon, 3.5 to 4.5 per cent hydrogen, and 6 to 13 per cent oxygen.

PROCESSING CHARACTERISTICS AND MINEABILITY

Although work on the processing characteristics of the Eagle Point ore is in progress, several points are noteworthy at the present time.

The Eagle Point deposits differ significantly from typical unconformity-type deposits in that nickel and arsenic are absent. They are essentially monomineralic uranium occurrences with few impurities which would affect the amenability of mineralization to processing.

Also, little chemical variation exists within the deposits, and blending of ore will not be required prior to processing except to maintain a uniform mill grade (chemical variations characterize some unconformity-type deposits such that a complex blending and grade-control process is required, adding to overall production costs).

Hydrothermal alteration at Eagle Point is generally restricted to mineralized zones, so the host rocks are relatively competent. The exploitation of the deposit is therefore likely to utilize, for the most part, conventional underground mining techniques. This situation is most fortuitous in that, while alteration and fracturing are of considerable benefit in open-pit mining situations, they are disadvantageous in underground operations where specialized mining methods would probably be required, increasing operating costs (deeply buried unconformity-type deposits, such as Cigar Lake, Midwest and McClean Lake, fall into this latter category).

The absence of extensive significant clay alteration at Eagle Point should result in an easily handled and easily processed ore.

RESERVES

The total ore reserves of the U_3O_8 combined Eagle Point deposits are approximately 140 million pounds (64,000 tonnes), at an average grade of about 2.0 per cent U_3O_8 . Some potential exists for adding to the Eagle North reserves, and the Eagle South deposit is not closed off down dip, so the total reserves are likely larger than those so-far proven, and might approach the size of Key Lake. Three-dimensional geostatistical reserve estimations have been completed on Eagle North and are in progress on Eagle South, where a narrower data base is available.

GEOCHRONOLOGY

U/Pb age determinations on five high-grade uranium samples were commissioned by GMCL in 1981. Fischer (1982) has interpreted the results as follows:

- the two generations of uraninite are dated at 1000 to 1400 Ma and at 450 to 700 Ma, with the older probably 1400 ± 25 Ma; and
- two generations of pitchblende are dated at 500 to 700 Ma and 5 to 20 Ma.

No further work has been done on the ages of the mineralization. The uranium in some zones and certain fracture orientations may be of a different age than that in the main zones, but this possibility has not yet been confirmed.

CLASSIFICATION AND ORIGIN OF THE DEPOSIT

The Eagle Point uranium deposits have many features in common with such well known "unconformity-type" deposits in the Athabasca Basin as Cigar Lake, Key Lake, Collins Bay B-Zone, and others. In varying degrees of similarity, these features include:

- 1) the ages of the several generations of uranium oxide;
- 2) the age and stratigraphic relationships of the metasedimentary rocks in the deposit area;
- 3) relative proximity to the inferred position of the Helikian paleosurface;
- 4) the grades of mineralization; and
- 5) the mineralogy and chemistry of the alteration directly related to mineralization.

Eagle Point is therefore interpreted to be a variant of the unconformity-type deposit, with the following significant differences:

- 1) the deposit is hosted entirely by Aphebian rocks;
- 2) the mineralization is simple, with no large quantities of other metals;
- 3) the mineralization extends for a considerable distance down dip from the inferred position of the Helikian paleosurface; and
- 4) the shapes of the main zones are more tabular and/or equidimensional than pencil-like (as at Cigar Lake, for example).

Three principal models of the origin of the Athabasca Basin unconformity-type uranium deposits are currently postulated. These models, which differ in their concepts of the time and mechanism of primary uranium deposition or pre-concentration, the source of the uranium, and the degree and timing of later modification, are:

- 1) the supergene model, first outlined by Knipping (1974);
- 2) the diagenetic-hydrothermal model, first formulated in print by Hoeve and Sibbald (1978); and
- 3) a syngenetic model of primary accumulation, incorporating significant metamorphic-hydrothermal upgrading and some aspects of the first two models.

The supergene model suggests that the deposits were created primarily by surficial processes at or near the subaerial paleosurface during Helikian weathering and/or during deposition of the Athabasca Group sediments. Uranium was mobilized by oxidizing ground water during the weathering of (U-enriched?) metasediments and/or granitic rocks, and was deposited in permeable fault zones and/or karsted topographic sinks. Uranium was deposited by reducing conditions created by graphitic, sulphidic host rock or by electrolysis, in part generated by a conductive host rock (Robertson et al, 1978). In this model, the Athabasca cover

served primarily as a protective cap to preserve the deposit from erosion. The model advocates allow that post-Athabasca faulting, burial metamorphism, mafic intrusives, and diagenesis may all have modified the pre-existing deposits to present ore grades and metal accumulations. This mechanism of deposit formation is invoked for Rabbit Lake (Knipping, 1974; Heine, 1986).

The diagenetic-hydrothermal model, first outlined in print by Hoeve and Sibbald (1978), emphasizes the role of oxidizing, uranium-bearing, diagenetic solutions from the Athabasca Group interacting with, at or near the Helikian unconformity, reductant-bearing solutions migrating upward through fracture systems in the Aphebian rocks. This model of deposit formation is invoked by Jones (1980) for the Collins Bay A- and B-Zones; by Hoeve and Quirt (1984) for Midwest; with some modification, by Wallis et al (1983) for the McClean deposits; by Laine (1986) for the deposits of the Carswell Structure; and by Harper et al (1986) for the Maurice Bay deposit.

The third model invokes syngenetic accumulation during Aphebian sedimentation and probable upgrading during the Hudsonian Orogeny, followed by important episodes of supergene and/or diagenetic upgrading. De Carle (1986) and Clarke and Fogwill (1986) propose this type of complex history for Key Lake and Dawn Lake respectively.

Each of these theories of origin has been considered for the Eagle Point deposits, but insufficient diagnostic data exist at this time to permit any definitive conclusion.

CONCLUSIONS

The Eagle Point deposits occur entirely within Wollaston Group rocks of Aphebian age. They are essentially structurally controlled, and are remarkably similar to each other in their simple mineralogy, consisting essentially of uranium oxide. Nickel, arsenic, cobalt, boron and other metals, which are characteristically present in typical unconformity-type deposits and which are contaminants as far as processing is concerned, are lacking.

At Eagle South, the mineralized zones are hosted by a complex structural system of anastomosing faults, located above the Collins Bay Fault. The Eagle Point Fault is not well defined at this deposit.

At Eagle North, most of the mineralization occurs above the Eagle Point Fault in near-vertical structures which strike at about 080°. The mineralization is contained in three mineralized zones. The 02 Zone, containing the largest portion of the reserves, is about 700 ft (213 m) in length and 250 ft (76 m) in width in vertical projection, and is about 1000 ft (300 m) deep in the vertical dimension.

Phyllosilicate alteration is characteristic of the mineralized zones, but is strongly developed only in close proximity to the mineralization. Alteration is, therefore, not very useful as an exploration tool.

The hosting units are relatively competent. The deposits are therefore likely to be successfully exploited utilizing conventional mining techniques.

The total ore reserves as determined by geostatistical methods for Eagle Point are about 140 million pounds (64,000 tonnes)

of U_3O_8 at a grade of about two per cent. Considerable potential exists for enlarging the Eagle South deposit as the main zones remain open down dip where they have been drill tested only to a depth of about 1000 feet (300 m). Smaller zones, stratigraphically higher, also remain open.

Less potential for significantly increasing reserves exists at Eagle North, where more drilling has been carried out.

REFERENCES

- Appleyard, E.C., 1981, Calc-silicate rocks and associated metasomatites of the Wollaston Group, in J.E. Christopher and R. Macdonald, eds., Summary of Investigations, 1981, Saskatchewan Geological Survey: Saskatchewan Mineral Resources Miscellaneous Report 81-4, p. 44-46.
- Clarke, P.J., and W.D. Fogwill, 1986, Geology of the Dawn Lake uranium deposits, northern Saskatchewan, in E.L. Evans, ed., Uranium Deposits of Canada: Canadian Institute of Mining and Metallurgy Special Volume 33, p. 134-143.
- De Carle, A.L., 1986, Geology of the Key Lake deposits, in E.L. Evans, ed., Uranium Deposits of Canada: Canadian Institute of Mining and Metallurgy Special Volume 33, p. 170-177.
- Fischer, P., 1982, Geology of the Eagle Point Uranium Deposit, Northern Saskatchewan: Fischer Geological Consulting Associates Ltd., report for GMCL (restricted circulation).
- Harper, C.T., R.P. Taylor and B.J. Fryer, 1986, Geology and lithogeochemistry of the Maurice Bay uranium deposit, northern Saskatchewan, in E.L. Evans, ed., Uranium Deposits of Canada: Canadian Institute of Mining and Metallurgy Special Volume 33, p. 241-249.
- Heine, T.H., 1986, The geology of the Rabbit Lake uranium deposit, Saskatchewan, in E.L. Evans, ed., Uranium Deposits of Canada: Canadian Institute of Mining and Metallurgy Special Volume 33, p. 134-143.
- Hoeve, J., and T.I.I. Sibbald, 1978, On the genesis of Rabbit Lake and other unconformity-type uranium deposits in northern Saskatchewan, Canada: Economic Geology, v. 73, p. 1450-1473.
- Hoeve, J., and D. Quirt, 1984, Uranium mineralization and host rock alteration in relation to clay mineral diagenesis and evolution of the middle-Proterozoic Athabasca Basin, northern Saskatchewan, Canada: Saskatchewan Research Council Publication R-855-2-A-84, 138 p.
- Jones, B.E., 1980, The geology of the Collins Bay uranium deposit, Saskatchewan: Canadian Institute of Mining and Metallurgy Bulletin, v. 73, no. 818, p. 84-90.
- Knipping, H.D., 1974, The concepts of supergene versus hypogene emplacement of uranium at Rabbit Lake, Saskatchewan, Canada, in The Formation of Uranium Deposits: International Atomic Energy Agency Symposium Volume, p. 531-549.
- Laine, R.T., 1986, Uranium deposits of the Carswell Structure, in E.L. Evans, ed., Uranium Deposits of Canada: Canadian Institute of Mining and Metallurgy Special Volume 33, p. 155-169.
- Landais, P., and J.M. Dereppe, 1985, A chemical study of the carbonaceous material from the Carswell structure, in R. Laine, D. Alonso, and M. Svab, eds., The Carswell Structure Uranium Deposits, Saskatchewan: Geological Association of Canada Special Paper 29, p. 165-174.
- Langford, F.F., 1986, Geology of the Athabasca Basin, in E.L. Evans, ed., Uranium Deposits of Canada: Canadian Institute of Mining and Metallurgy Special Volume 33, p. 123-133.
- Macdonald, C.C., 1980, Mineralogy and geochemistry of a Precambrian regolith in the Athabasca Basin: unpublished M.Sc. thesis, University of Saskatchewan, Saskatoon, 151 p.
- Ramaekers, P., 1983, Geology of the Athabasca Group, NEA/IAEA Athabasca test area, in E.M. Cameron, ed., Uranium Exploration in Athabasca Basin, Saskatchewan, Canada: Geological Survey of Canada Paper 82-11, p. 15-26.
- Ray, G.E., 1978, Reconnaissance geology, Wollaston Lake West area (part of NTS area 64L), in J.E. Christopher and R. Macdonald, eds., Summary of Investigations 1978, Saskatchewan Geological Survey: Saskatchewan Mineral Resources Miscellaneous Report 78-10, p. 25-34.
- Robertson, D.S., J.E. Tilsley, and J.M. Hogg, 1978, The time-bound character of uranium deposits: Economic Geology, v. 73, p. 1409-1419.
- Sibbald, T.I.I., 1983, Geology of the crystalline basement, NEA/IAEA Athabasca test area, in E.M. Cameron, ed., Uranium Exploration in Athabasca Basin, Saskatchewan, Canada: Geological Survey of Canada Paper 82-11, p. 1-14.
- Sopuck, V.J., A. de Carle, E.M. Wray, and B. Cooper, 1983, Application of lithogeochemistry to the search for unconformity-type uranium deposits in the Athabasca Basin, in E.M. Cameron, ed., Uranium Exploration in Athabasca Basin, Saskatchewan, Canada: Geological Survey of Canada Paper 82-11, p. 191-205.
- Thomas, M.W., 1982, Compilation bedrock geology: Wollaston Lake area (NTS 64L), in R. Macdonald, T.I.I. Sibbald, D.F. Paterson, P. Guliov, and J.V. Buller, eds., Summary of Investigations 1982, Saskatchewan Geological Survey: Saskatchewan Energy and Mines Miscellaneous Paper 82-4, p. 2-5.
- Wallis, R.H., 1971, The geology of the Hidden Bay area, Saskatchewan: Saskatchewan Department of Mineral Resources Report 137, 74 p.
- Wallis, R.H., N. Saracoglu, J.J. Brummer, and J.P. Golightly, 1983, Geology of the McLean uranium deposits, in E.M. Cameron, ed., Uranium Exploration in Athabasca Basin, Saskatchewan, Canada: Geological Survey of Canada Paper 82-11, p. 71-110.

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GEOLOGY OF THE CIGAR LAKE URANIUM DEPOSIT (SASKATCHEWAN, CANADA)

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ABSTRACT

The Cigar Lake uranium deposit occurs in the Athabasca Basin of northern Saskatchewan. It was discovered in 1981 by Cogema Canada Limited, operator of the Waterbury Lake joint venture (S.M.D.C., Idemitsu Exploration Canada Limited and Cogema Canada Limited).

By the end of 1985, the orebody had been delineated by 170 drill holes of which 118 were mineralized. The total geological reserves are estimated to be 150,000 metric tonnes of uranium metal at an average grade of eight per cent.

Although the orebody shares many features with several other deposits in the region, it is characterized by its location in Athabasca Group sandstones, its continuity, the intensity of alteration processes, and the presence of high-grade massive mineralization.

The deposit is spatially related to the major unconformity separating the Helikian Athabasca Group from Aphebian graphitic metasediments of the Wollaston Group. It occurs at an average depth of 430 metres as a flattened, east-west elongated body extending over a length of 2,150 metres. In its eastern part, where most of the mineralization is concentrated, the ore zone reaches a maximum width of 100 metres and maximum thickness of 20 metres. A well defined ridge of basement rocks underlies the mineralized zone over its entire length.

The Athabasca Group, where it hosts the Cigar Lake deposit, consists of micro-conglomeratic sandstones corresponding to units D, C and B of the Manitou Falls Formation. The metamorphic basement below the deposit comprises a steeply south-dipping belt of east-west trending, augen-textured pelitic gneisses, which coincide exactly with the afore-mentioned ridge, surrounded by fine-grained gneissose pelites with calc-silicate layers. This graphite- (5 to 10 per cent) and sulphide- (1 to 5 per cent) rich belt is interpreted as a mylonitic zone of Hudsonian age. The mineral assemblages include sillimanite, cordierite and garnet and indicate that the amphibolite facies was reached during regional metamorphism of the basement rocks.

The deposit is enveloped by extensively altered rocks. In the basement, hydrothermal alteration (illitization, chloritization, development of dravite-phosphates-calcite) is superimposed upon previous retrograde and regolithic alterations. In the sandstones, alteration processes display concentric zones generally extending up to about 300 metres above the orebody. They consist, from top to bottom, of bleaching, grey alteration (sulphide impregnations), euhedral quartz crystal growths, and argillization (illite) with massive quartz dissolution and intense fracturing. The orebody is commonly capped by a zone of hematized massive clay (illite, Fe-rich illite and Mg-rich illite) containing siderite and hydrocarbons.

The orebody consists of a massive high-grade core surrounded by a lower grade envelope. Mineralization may extend upwards along steeply dipping faults in the sandstones ("perched mineralization"), and is interpreted to be late-stage remobilization of the unconformity ore. Such extensions are of limited importance in the basement.

The high-grade core is characterized by an association of pitchblende and Ni-Co arsenides. The clay matrix ("indurated clay") contains Fe-chlorite, Mg-chlorite and a newly discovered Fe-rich clay mineral, here informally named "ferri-kaolinite". At least three stages of ore formation are recorded, as for other deposits of the area, with the first and main event dated at 1300 Ma.

INTRODUCTION

The Cigar Lake uranium deposit is located in the Athabasca Basin of northern Saskatchewan, Canada (Fig. 1). It was discovered in 1981 by Cogema Canada Limited (previously

Seru Nuclear Canada Limited), as operator of the Waterbury Lake Joint Venture (Saskatchewan Mining Development Corporation, or S.M.D.C., 50.75 per cent; Cogema Canada Limited, 32.625 per cent; Idemitsu Exploration Canada Limited, 12.875 per cent; and Corona Grande Exploration

Corporation, a wholly owned subsidiary of Cogema, 3.75 per cent).

In 1985, the joint venture owners formed an operating company, the Cigar Lake Mining Corporation (C.L.M.C.), to develop the deposit for production in the early 1990s (Fouques and Tosney, 1985).

The Cigar Lake uranium deposit is spatially related to the major unconformity between the Athabasca Group sandstones and the crystalline basement rocks. Although it shows many similarities to several other uranium deposits of the Athabasca Basin, (e.g. McClean Lake, Midwest, Collins Bay and Key Lake), it is characterized by its location entirely in sandstone, its continuity, its intensity of host-rock alteration and its thick high-grade massive mineralization (Bruneton and Caumartin, 1985).

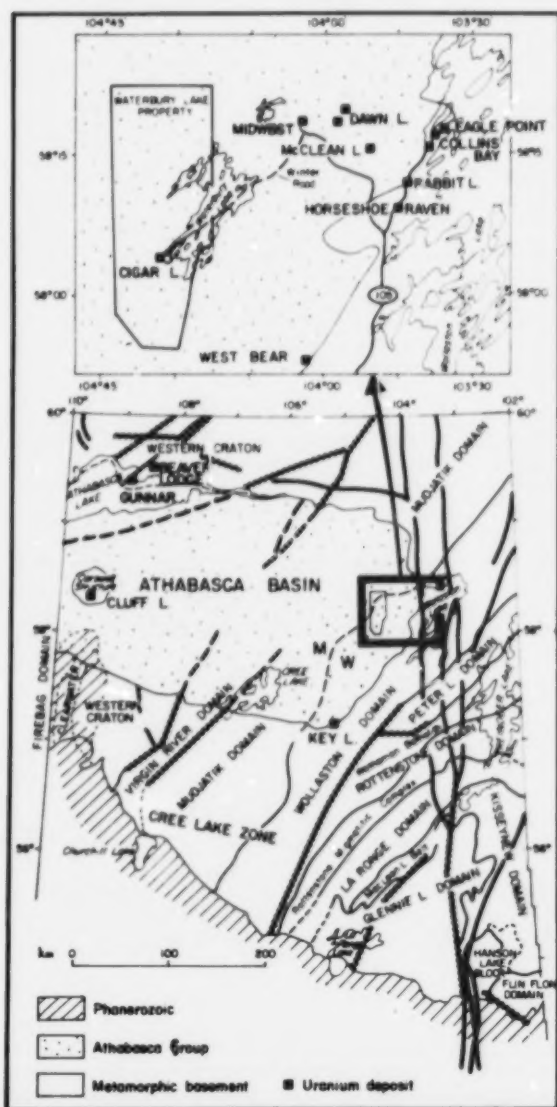


Figure 1. Location of the Cigar Lake uranium deposit.

REGIONAL GEOLOGY

The geological environment of the Cigar Lake deposit is comparable to that of other major uranium deposits of the area. It is situated well inside the Athabasca Basin (Fig. 1), at the unconformity between metasediments of the Wollaston Group and detrital units of the unmetamorphosed Helikian Athabasca Group.

The Wollaston Group, an Aphebian supracrustal succession (Ray, 1975), overlies remobilized Archean basement. The age of this Aphebian metamorphic sequence is between 2500 and 1850 Ma with a probable metamorphic peak around 1875 Ma (Bell and Macdonald, 1982). The Athabasca Group has been dated at 1430 Ma by Armstrong and Ramaekers (1984) using samples from the tuffaceous Wolverine Point Formation.

The Wollaston Group has been divided into three major stratigraphic units: a lowermost pelitic-semipelitic unit which is in part graphitic, overlain successively by units dominated by meta-arkosic rocks and by interlayered sillimanitic quartzites, amphibolites and calc-silicates (Sibbald, 1983). During the Hudsonian Orogeny, these lithologies underwent polyphase deformation and low- to intermediate-pressure upper amphibolite facies metamorphism. Two main deformational events have been recognized; folding during the second of these produced NE-SW elongated domes and basins.

Interpretation of aeromagnetic surveys places the Cigar Lake area in a Wollaston Domain pelitic zone, presumed to occur at the base of the Wollaston Group (Fouques et al, 1986). This location lies about one kilometre south of an interpreted Archean granitic dome (Fig. 2). The pelitic unit is composed of fine-grained garnet-cordierite-graphite-biotite gneisses with intercalations of amphibolitic gneisses and calc-silicate rocks. Within the pelitic unit, geophysical conductors coincide with rock layers enriched in graphite and sulphides. The orebody is located above one of these geophysical conductors.

SUMMARY OF WORK DONE AND DRILLING TECHNIQUES USED

In May 1981, the first mineralized drill hole (WDG1-15) penetrated the western part of the orebody (Fig. 3) while testing a geophysical conductor. In 1982, the drilling program, which consisted of 25 drill holes, was concerned mostly with the "West Zone" and resulted in the rough delineation of the shape and trend of the orebody.

In 1983 and 1984, 110 drill holes were completed following a 20m x 50m grid spacing in the "East Zone" (lines 3 + 50E to 12 + 50E). Two lines, 7 + 50E and 9 + 50E, used a 10m spacing between holes to test the spatial continuity of the orebody. Additional fences were drilled on the western extension using a 20m x 200m spacing. One exploration fence consisting of three holes with 50m spacing was drilled to the east of the ore zone (line 15 + 50E).

The 1985 and 1986 programs consisted of the closing off of the west side, the testing of possible lateral extensions, and the beginning of geotechnical work in preparation for a feasibility study of the "East Zone". By July 1986, the Cigar Lake deposit had been delineated and explored with 170 diamond drill holes, 118 of which were mineralized. An additional 41 geological drill holes had also been completed either in the immediate vicinity of the orebody or to explore new zones.

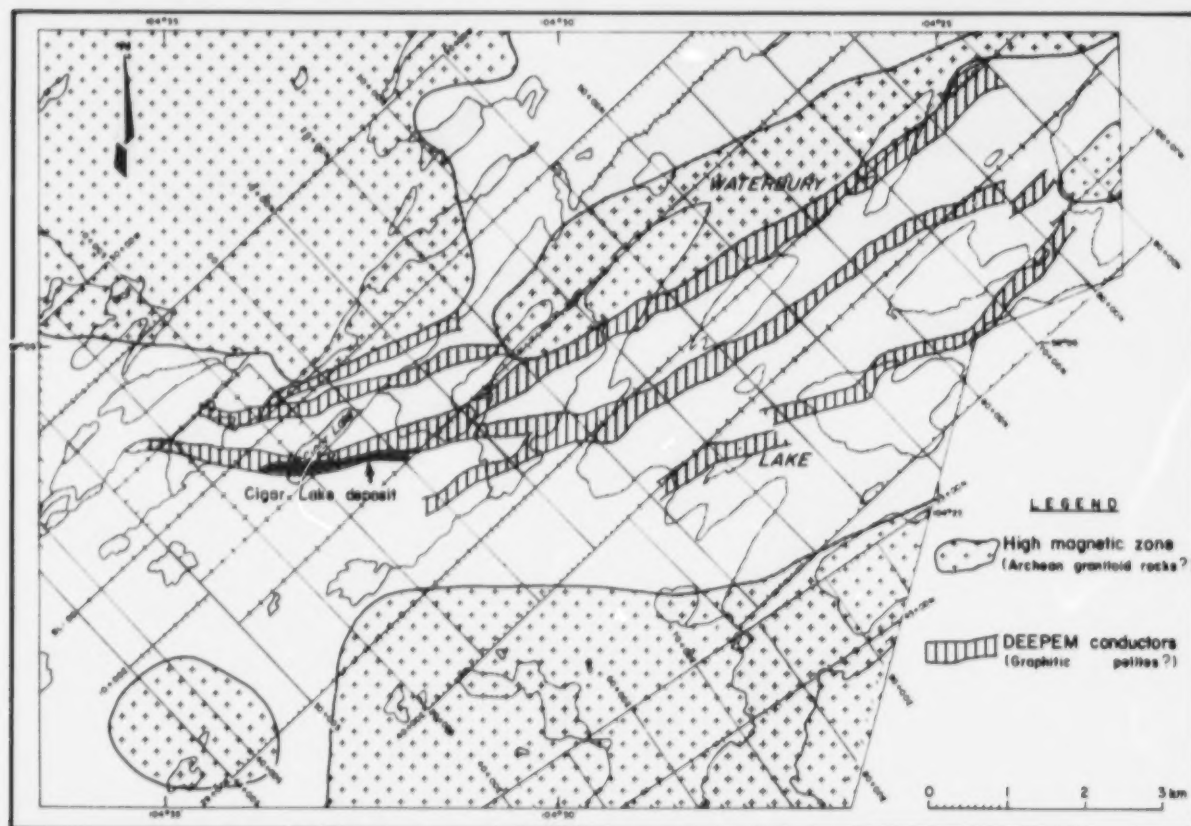


Figure 2. Geophysical interpretation of the basement rocks in the Cigar Lake area (modified after Fouques et al., 1986).

Longyear 38 or 44 rigs were used to complete the drilling program. All the drill holes were vertical, except for six which were inclined (60°) to obtain structural information (Fig. 3).

The overburden was drilled using HQ diamond coring and tricone bits. Sandstone was recovered using NQ diamond coring and a three-metre core barrel. NQ 3 bits and the five-foot triple-tube coring method were used in the zone of interest (from 400 m, through the mineralization) in an attempt to optimize core recovery and minimize disturbance of the core.

Drill-hole deviations were measured accurately using two methods:

- 1) a Sperry Sun single-shot camera fired at 50m intervals to follow the path of a drill hole during drilling, and
- 2) an Eastman Kodak multishot camera after the end of drilling.

The second method gives inclination and azimuth data at specific depth intervals (every nine metres at Cigar Lake) from the bottom to the top of the hole.

In 1982 and 1983, several intersections of the sub-Athabasca unconformity were obtained from a single hole using wedges at different depths. This method was later abandoned due to

difficulties in setting wedges in the fractured areas surrounding the orebody. If the drill-hole deviation exceeded one degree during penetration of the higher sections of sandstone, wedges were used in order to obtain a regular grid pattern at the unconformity.

All the drill holes have been probed with neutron-neutron and natural gamma down-hole probe surveys, with additional ST22-2T probing in mineralized holes.

MAIN CHARACTERISTICS OF THE CIGAR LAKE OREBODY

The deposit, which is devoid of any direct surface expression, is located at 410 to 450m depth. It is a flat, elongated body displaying a remarkable continuity (Fig. 3). It is 2,150m long with a width of 25 to 100m and a maximum thickness of 20m.

Based on structural data, the deposit has been divided into two main portions. The "East Zone", between lines 3 + 50E and 11 + 50E, contains most of the mineralization (110,000 t of uranium metal at a minimum average grade of 12.3 per cent). This area has been explored using a 50m x 20m drilling grid (123 drill holes) and has produced most of the geological data reported here. The "West Zone" (or western extension), between lines 3 + 50E and 10 + 00W, contains reserves estimated at about 40,000 metric tons of uranium metal at an average grade of 4 per cent U, and has been drilled following a 200m x 20m grid (47 drill holes).

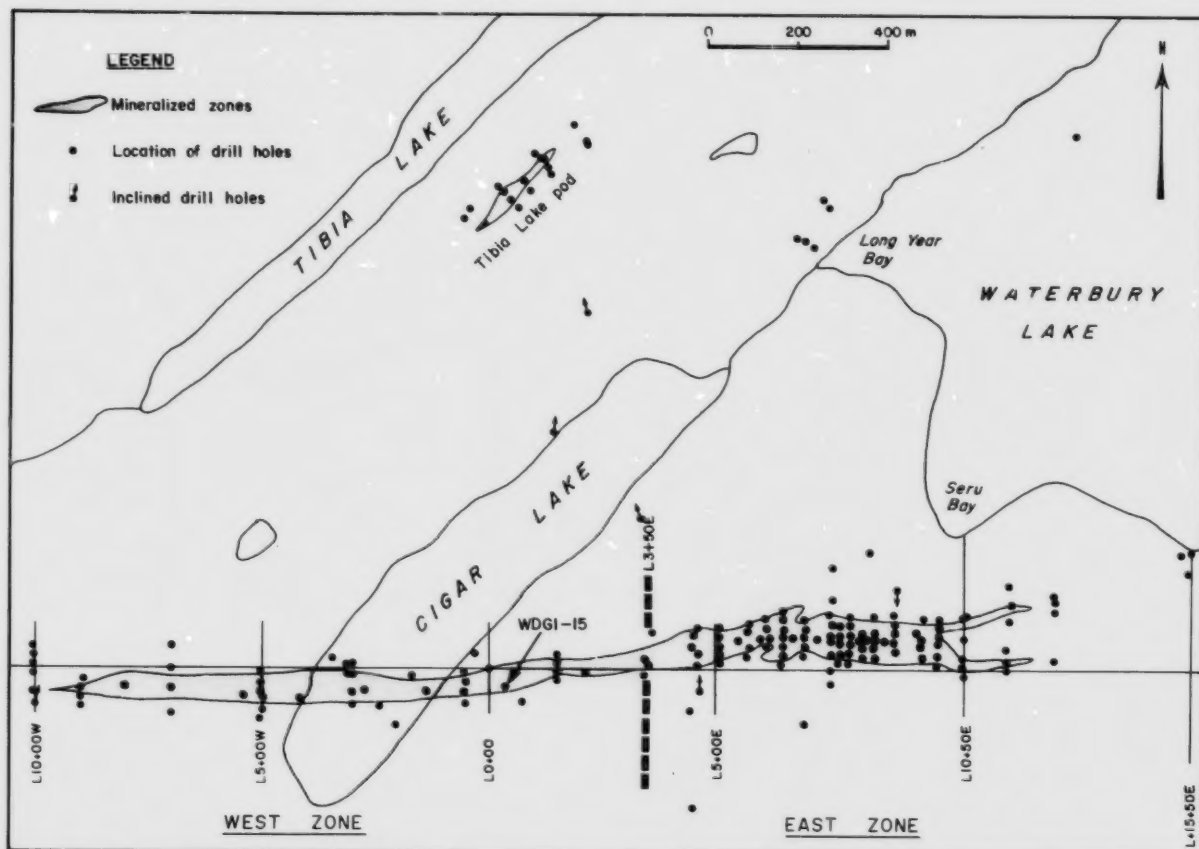
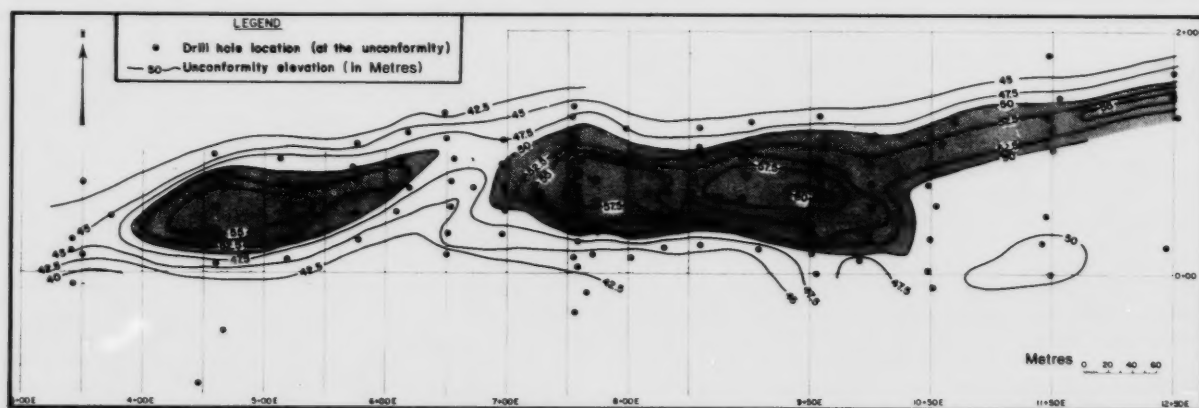


Figure 3. Location of drill holes and general outline of the Cigar Lake uranium deposit.

Most of the mineralization occurs in the basal Athabasca sandstone, just above the sub-Athabasca unconformity. However, some mineralization has been encountered up to 300m above the unconformity ("perched mineralization") and as veins in basement rocks. The veins are rare enough to be negligible in terms of ore tonnage, but the "perched mineralization" in the sandstone is sufficiently common to give locally significant metal accumulations.

The deposit is situated on top of a basement ridge which reaches a maximum relative elevation of 20m and which appears to control the distribution of ore (Figs. 4 and 5). On both sides where the orebody ends, the ridge also disappears. This results in a strong correlation between the present topography of the unconformity and the metal accumulation values.



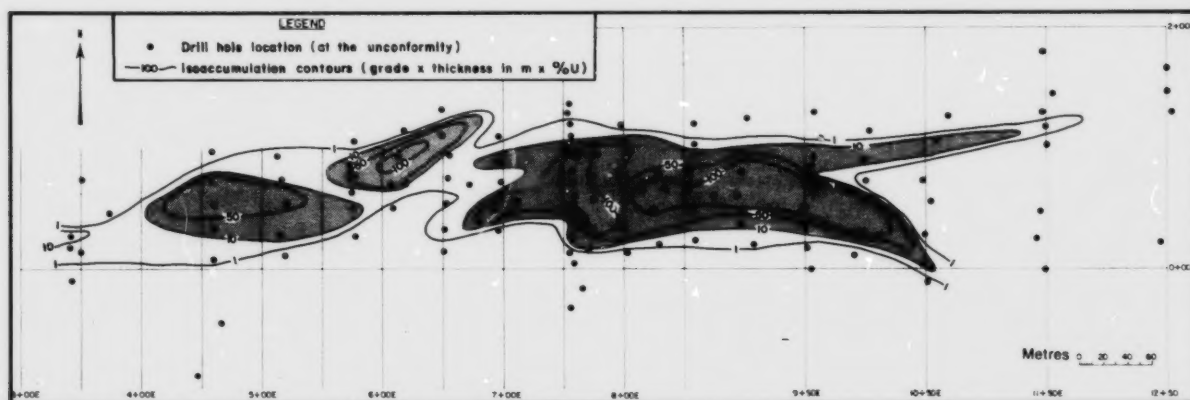


Figure 5. Contours of uranium accumulations at the unconformity, Cigar Lake "East Zone".

LOCAL GEOLOGY

At Cigar Lake, the Athabasca Group is approximately 400m thick. It is covered by a few tens of metres (maximum 55m) of glacial till (Fig. 6). The orebody, located at the contact between the Athabasca Group and metamorphic basement, is coincident with the subcrop of a steeply dipping, east-west trending, graphite-rich pelitic unit.

ATHABASCA GROUP

Based on the interpretation of down-hole probe surveys (neutron-neutron and natural gamma) and geological observations, the Athabasca Group has been divided into three main sedimentary units which correspond to units D, C and B of the Manitou Falls Formation (Ramaekers, 1981). The main geological characteristics of these formations, as summarized in Figure 7, are derived from observations made in drill hole WDG1-139 which, located 400m south of the orebody (Fig. 3), is not affected by hydrothermal alteration.

The Manitou Falls Formation, observed in drill core, consists of a monotonous sequence of sandstone with medium- to coarse-grained units low in the sequence and finer units towards the surface. It has been interpreted as a braided stream fluvial deposit, its sediments derived from the east (Ramaekers, 1983). The sandstone ranges in colour from pinkish grey to purple. A late, orange, limonitic alteration is superimposed on the uppermost 100m while grey to green colours (chloritization) appear in the 30m above the unconformity. Secondary quartz overgrowths are abundantly developed. Altered detrital biotite and muscovite are present, as are neoformed hematite and detrital heavy minerals. Conglomeratic layers containing pebbles up to 10cm in diameter are common in the lowermost 30m of the Athabasca Group, along with numerous heavy mineral beds dominated by specular hematite with some magnetite and minor amounts of zircon, rutile, leucoxene and tourmaline.

Recent work carried out by Ramaekers (1986) shows that conglomeratic layers form reliable marker horizons which may be followed for several kilometres on the Waterbury Lake property. The topographic ridge in the basement below the orebody is interpreted by the author as an Hudsonian paleohill, in part because the basal conglomeratic unit thins, then disappears, close to the orebody.

BASEMENT LITHOLOGY

The metamorphic basement, considered as part of the Wollaston Group, is divisible into two units:

- 1) graphite-bearing pelitic gneisses with biotite and cordierite, and
- 2) calc-magnesian gneisses with amphibole and pyroxene.

These two units are cut by leucocratic veins or masses of quartzofeldspathic anatectic pegmatoidal rock.

Structurally, the lithologic units appear to dip towards the south at angles ranging from 50° to 80°. Axial plane schistosity is strongly developed in the graphitic gneisses. Also, folds with amplitudes ranging from one metre to ten metres are present in drill core.

In the Cigar Lake area, graphitic gneisses are the predominant metasedimentary rock type, and have been divided into two main subunits:

- 1) augen-textured pelites ("augen gneisses"), and
- 2) fine-grained pelites.

The "augen gneisses" form an east-west belt about 100m wide. They are located below the mineralized body. The fine-grained pelites occur on either side of this belt, and in thin horizons within the "augen gneiss".

The fine-grained pelites are massive, and are dark in colour due to the presence of biotite and graphite. In the Cigar Lake area, they are strongly altered, their silicate minerals replaced by illite or an illite-chlorite mixture. The mineralogical composition of the fine-grained pelites is:

Quartz, 20 to 30 per cent

K-feldspar and plagioclase, 40 to 70 per cent

Biotite, 10 to 20 per cent

Cordierite, 5 to 15 per cent

Graphite, 1 to 3 per cent

Garnet, sillimanite and sulphides are present in places

Accessory minerals include apatite, monazite, zircon, ilmenite, rutile, and tourmaline.

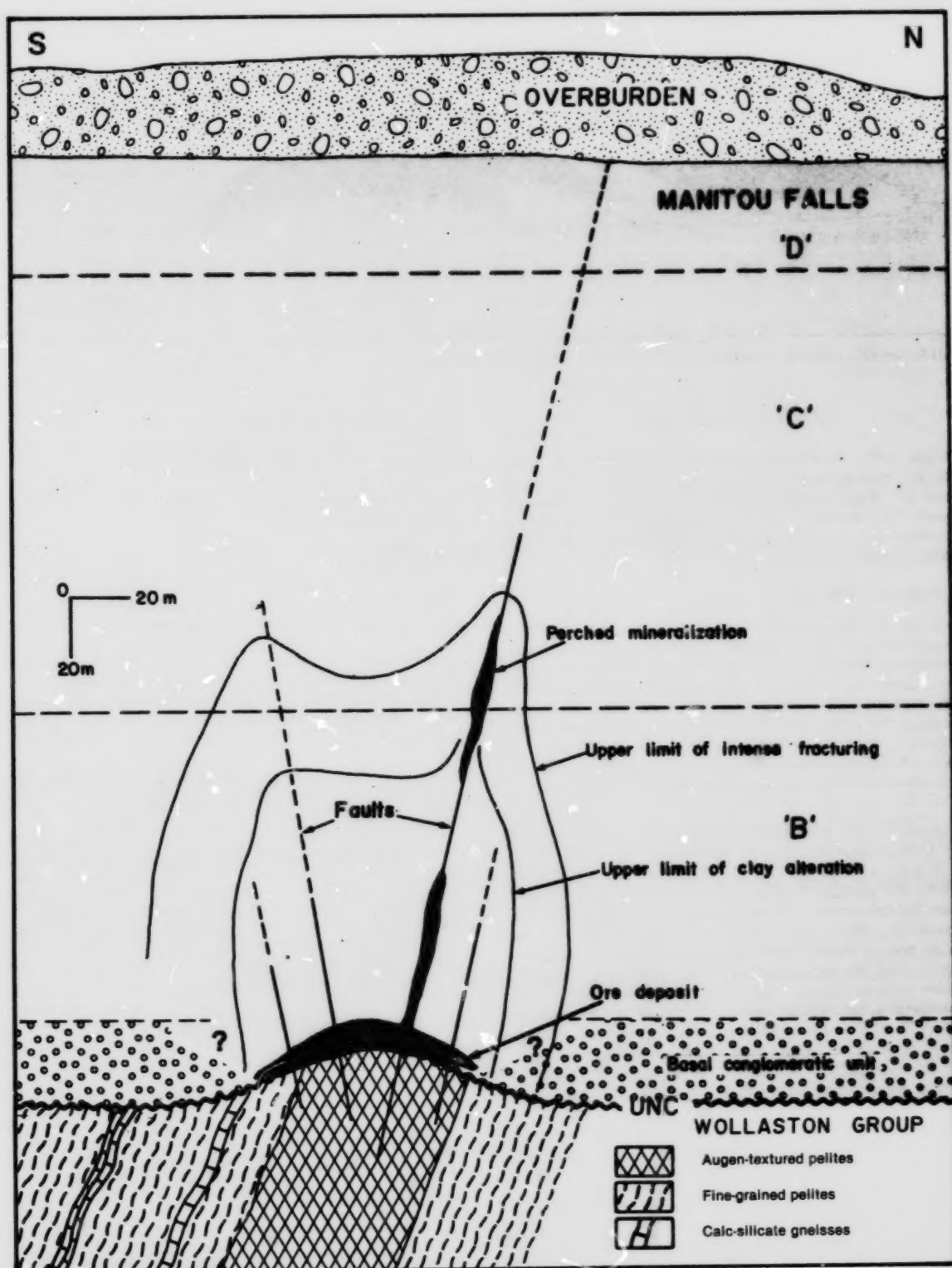


Figure 6. Schematic cross-section, Cigar Lake area.

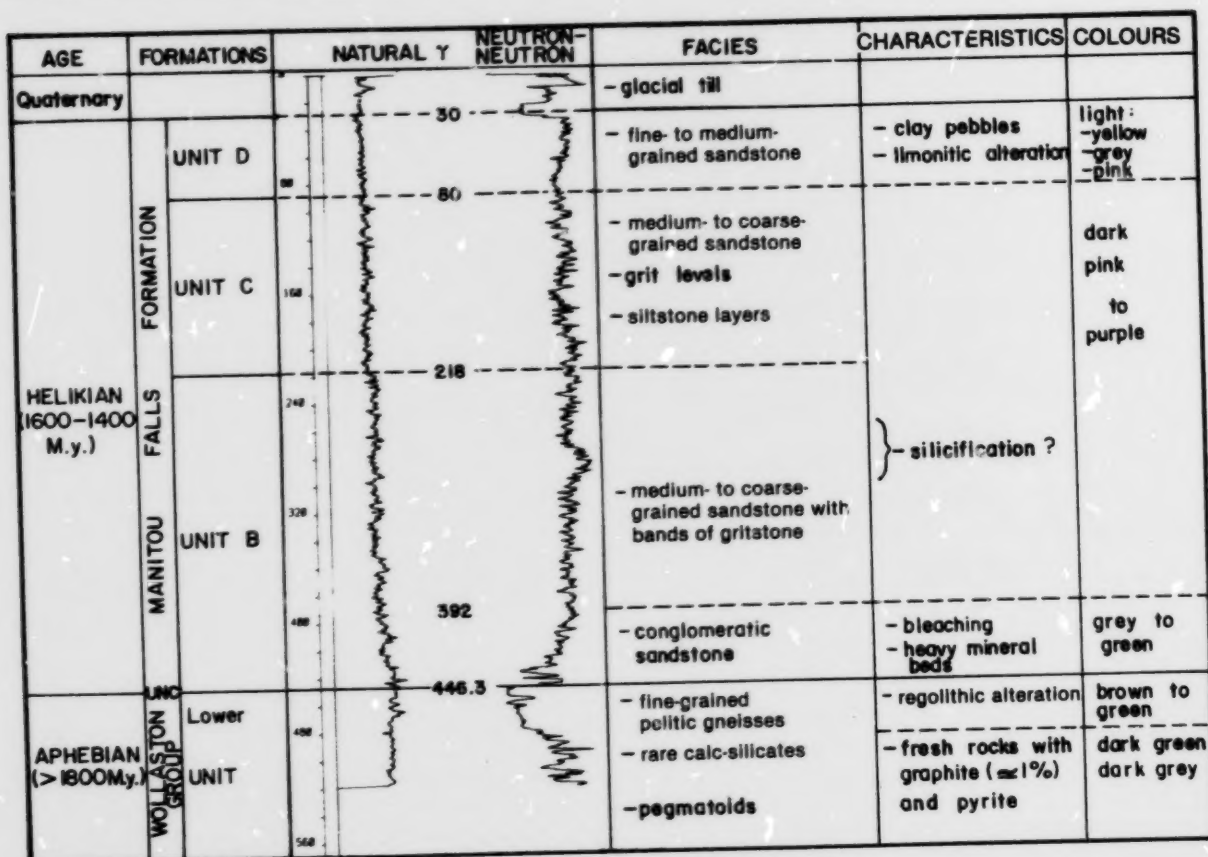


Figure 7. Schematic lithostratigraphy, Cigar Lake area, using drill hole WDG1-139, located south of the orebody.

The augen-textured pelites have a mineralogical composition similar to that of the fine-grained pelites, although the relative abundance of their constituent minerals may differ. Porphyroblasts (3 to 20mm in diameter) of cordierite and K-feldspar form dark green nodules with polygonal or fusiform shapes. They contrast sharply with the fine- to medium-grained matrix. The amount of graphite ranges from 3 to 10 per cent. The sulphides, mainly pyrite, constitute 1 to 5 per cent of the rock, with some local enrichment. The "augen gneisses", due to their location below the orebody, are everywhere intensely affected by hydrothermal alteration.

Calc-magnesian gneisses occur south of the orebody as thin massive layers or lenses intercalated with fine-grained pelites (Fig. 6). They are characterized by their heterogeneity in grain size, in texture, and in colour, and by their transitional nature into pelitic rock. In addition to plagioclase, the main constituent mineral, the gneisses contain calcic pyroxene (diopside), slightly altered amphibole, and phlogopitic mica which locally comprises up to 30 per cent of the rock. Accessory minerals sphene, zircon, apatite, monazite and tourmaline are abundant; some graphite is also common.

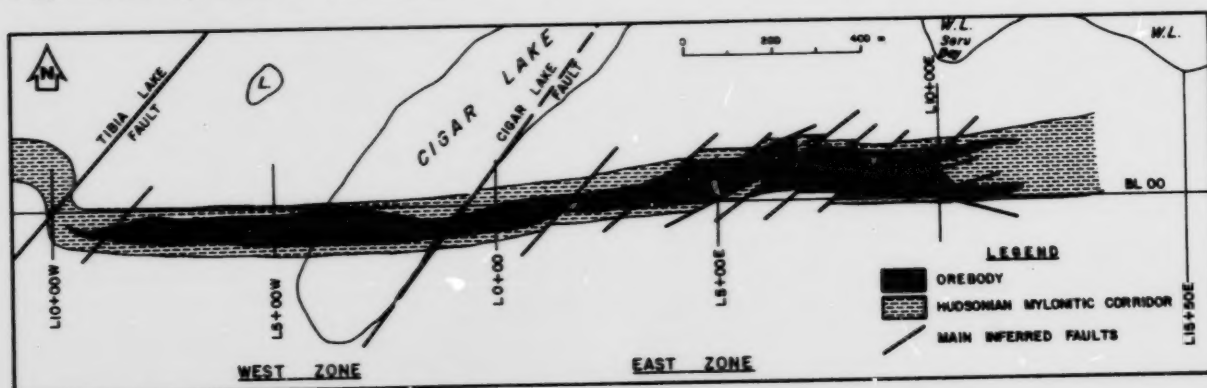


Figure 8. Interpretation of the geology of the basement at the unconformity, Cigar Lake area.

Pegmatoids or mobilizates are widely developed, and are diverse in morphology and grain size. They occur as irregular bodies which are concordant or discordant with the foliation, and are quartzofeldspathic in composition (K-feldspar dominant). They contain various other minerals such as cordierite, sillimanite, garnet, muscovite, graphite, and sulphides. The mineralogical and textural characteristics of the pegmatoids suggest their local origin, probably from anatectic melting of the surrounding pelites.

The following petrographic observations suggest that the rocks attained upper amphibolite grade during regional metamorphism:

- absence of primary muscovite,
- presence of sillimanite,
- cordierite-garnet association, and
- common anatectic quartzofeldspathic mobilizates.

The metamorphic rocks below and around the Cigar Lake orebody have been intensely altered by one or more processes:

- retrograde metamorphism during the late stages of the Hudsonian Orogeny,
- alteration related to the development of pre-Athabasca paleoweathering, and
- hydrothermal alteration superimposed upon the other alterations and extending up into overlying sandstones.

ALTERATION

1. RETROGRADE METAMORPHIC ALTERATION

Retrograde metamorphic alteration, not a major feature, is characterized below the regolith by the sericitization and chloritization of cordierite, the sericitization of feldspar, and the slight chloritization of biotite, amphibole and garnet.

2. PRE-ATHABASCA PALEOWEATHERING

Pre-Athabasca paleoweathering is well developed on the crystalline basement rocks away from the orebody. In most of the drill holes, three colour zones have been recognized:

- *an orange to yellow zone*, generally thin (0.5 to 2 m), but locally absent, located directly below the unconformity and mainly composed of quartz grains floating in a kaolinite matrix;
- *a red oxidized zone* extending down to about 20 to 25 m below the sub-Athabasca unconformity, and characterized by abundant iron oxides (hematite) and anatase and by the lack of graphite and sulphides; metamorphic minerals have been destroyed and replaced by clay minerals such as kaolinite, illite, and, rarely, chlorite;
- *a green zone*, transitional between the red zone and the fresh unweathered basement below, displaying a composite character due to the combination of retrograde and paleoweathering processes; original textures and minerals are clearly recognizable, and graphite and sulphides are present in pelitic rocks; typical alteration minerals are illite, Mg-rich illite and Fe-chlorite.

The paleoweathering profile is similar to that described elsewhere in the Athabasca Basin (Hoeve and Sibbald, 1978,

Macdonald, 1985). Its thickness varies according to the type of parent rock, as variations in original mineralogy and texture apparently influence the degree of paleoweathering (Ibrahim and Woo, 1985; Mellinger, 1985), which, within the Waterbury Lake permit area, is well developed in the calc-silicate and fine-grained pelitic gneisses (40 to 60 m thick), but poorly developed in coarse-grained graphite-bearing pelitic gneisses where the orange and red zones are generally absent.

3. HYDROTHERMAL ALTERATION

Hydrothermal alteration surrounds the deposit, affects basement rocks down to about 100 m below the unconformity, and extends upwards about 300 m into the sandstone. This alteration in the sandstone displays concentric zones which consist of, from top to bottom (Fig. 9):

- *bleaching (B)*; this reaches to the surface of the sandstone where late limonitic alteration has been superimposed upon the bleaching;
- *grey alteration (G1)*; the colour is due to micro-dissemination of iron sulphides (mainly marcasite) and, in places, of hydrocarbons;
- *a quartz zone (G1+Q)*, or zone of quartz precipitation, characterized by a grey colour, and by fracturing with euhedral quartz crystals filling most of the fractures;
- *grey alteration (G2)* with strong fracturing and appearance of clay (illite) in the matrix of the sandstone and along fractures;
- *clay alteration (CL)*, where the clay content progressively increases (forming up to 30 per cent of the rock by volume) towards the orebody; the sandstone becomes friable, producing locally unconsolidated sand (zone of quartz dissolution),

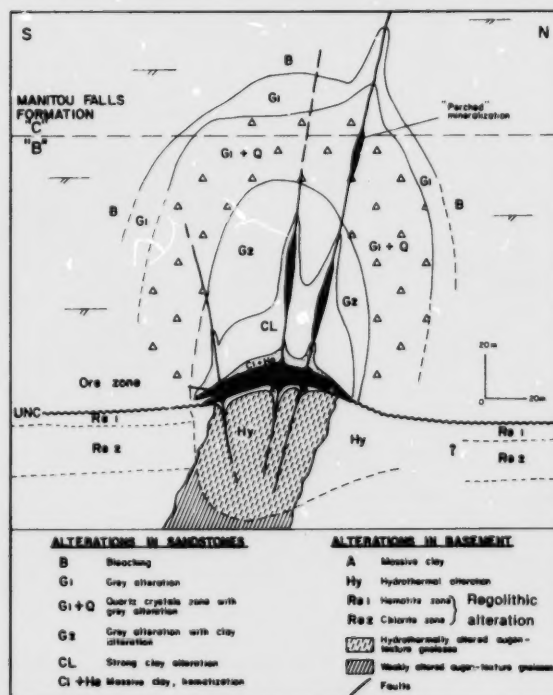


Figure 9. Alteration zones around the Cigar Lake uranium deposit.

and core loss may result in some drill holes; the appearance of massive irregular "soft clay" layers or pockets in this zone seems to be directly related to the presence of faults; the dominant clay mineral is illite;

- *the massive clay zone* (CL + HE) capping the massive ore zone is almost entirely composed of clay with rare sandstone remnants; oxidized areas are common and siderite is locally abundant either as aggregates of euhedral crystals or as irregular layers; this zone is weakly mineralized (0.01 to 1 per cent U) but local concentrations of several per cent uranium are present; good spatial continuity is apparent in the east part of the orebody where the zone reaches a maximum thickness of 12 m;
- *the massive ore zone* has sharp contacts with the massive clay zone above and with the argillized basement below; the outstanding characteristic of this zone is its very high uranium content which may exceed 50 per cent over several metres; the zone is composed of brecciated pitchblende associated with sulphides and sulpharsenides; oxidation (red colouration) is limited to faults; the clay matrix is represented by dark grey to dark green clays.

Contacts between successive alteration envelopes in the sandstone are disturbed by steeply dipping faults which reach the surface in some cases. "Perched mineralization" is located along some of these faults. A red colour due to secondary oxidation may appear in clay alteration zones along the faults.

In the basement, hydrothermal alteration, observed up to 100 m below the orebody, totally obliterates earlier alterations. Two main zones have been identified (Fig. 9):

- **totally argillized basement (A)**, located immediately below the richest part of the orebody, one to three metres in thickness but thicker where faulted; pale to moderate green in colour; weakly mineralized; all original texture has disappeared and neither graphite nor pyrite is present;
- **altered basement** in which original textures are visible; minerals such as biotite, amphibole, garnet and feldspar are strongly altered to Mg-rich and Fe-rich illite and Mg-Fe-chlorite; graphite and pyrite are present; secondary minerals such as dravite and various phosphates are widespread.

Clays related to hydrothermal alteration have been divided into four main types on the basis of both geological and geotechnical criteria. In sandstone, they have been classified as "soft", "intermediate" and "indurated"; in the basement, they are termed "basement clays".

- **"Soft" clays** are located above the massive clay cap and have irregular distribution. They occur as layers along bedding planes, as massive irregular pockets locally reaching thicknesses of several metres, and as "veins" along steeply-dipping faults and fractures wrapping sandstone blocks. Bedding is generally well marked by thin dark beds of heavy minerals, and cross-bedding is commonly preserved. "Soft" clays are white, pale yellow, pale green or pale grey in colour. They are mainly composed of illite and are consistent in composition (Table 1). The small amount of uranium observed (10 to 300 ppm U) is explicable by absorption phenomena on clay layers.

- **"Intermediate" clays** are the clay-type most commonly encountered in mineralized drill holes. They represent an intermediate category between "soft" clays and "indurated" clays. Transitional facies between the three types of clays have been observed, generally with gradational contacts. "Intermediate" clays are the main component of the massive clay cap. They are closely associated with, or have replaced, "indurated" clays. They also form a matrix for mineralization, and occur as a layer between massive pitchblende and argillized basement. In the latter situation, the clays are normally rich in base metals and phosphate needles. Their colour ranges from pale green to pale or dark grey, and from red to brown in oxidized areas. Siderite and, locally, hydrocarbon buttons are abundant in reduced areas of this facies. "Intermediate" clays are composed of illite, Fe-rich illite, Mg-rich illite, Fe-chlorite and Mg-chlorite in differing proportions. Consequently, their chemical composition varies, especially for elements such as Fe₂O₃ (total), MgO and K₂O (Table 1). This category of clays is commonly mineralized, containing from 200 ppm to several per cent uranium.

- **"Indurated" clays** are related to secondary silicification or carbonation processes, are located in the massive clay cap, and are associated or intercalated with "intermediate" clays of dark green to dark brown colour. Siderite may form more than 50 per cent of the rock. The clay material is iron-rich (Table 1) and, typically, weakly mineralized. A second type of "indurated" clay, dark green to dark grey in colour, occurs as a matrix to massive ore. It seems to represent a primary facies and is, in places, replaced by later "intermediate" clay. "Indurated" clays of this second type are, in general, distant from inferred faults and are strongly mineralized. They may be the only clay material present in some drill holes. A third type of "indurated" clay has been observed along steeply dipping faults which crosscut sandstones. Dark green in colour, it looks like "vein" material, is mineralized, and is located in drill holes on the edge of the orebody. Like "intermediate" clays, "indurated" clays show variable mineralogical and chemical compositions according to their location and degree of oxidation. Mg-rich illite, Fe-rich illite, Mg-chlorite and Fe-chlorite have been observed in different amounts, and a mineral called "ferri-kaolinite" has also been locally observed. Further work is presently underway to identify more precisely the nature and structural characteristics of this last-named clay mineral, the properties of which are closer to those of kaolinite than to those of chlorite.

- **"Basement" clays** are essentially composed of Mg-chlorite (sudaite) and Mg-rich illite. MgO and K₂O values (Table 1) are high. Calcite may be locally abundant, along with black hydrocarbon buttons and white dravite veinlets.

Destruction of graphite and formation of hydrocarbon buttons have been reported in most uranium deposits of the Athabasca Basin. Hoeve and Quirt (1984) pointed out that the close connection between host-rock alteration, graphite destruction, hydrocarbon formation and mineralization favours an hydrothermal origin for hydrocarbon matter.

Table 1. Chemical composition of the four main types of clay associated with the main mineralization (values are in per cent for the major oxides, in ppm for the selected trace elements).

	"Soft" clay						"Intermediate" clay				"Indurated" clay	"Basement" clay	
SiO ₂	47.58	47.37	46.07	47.15	46.49	44.50	41.78	33.12	36.03	32.49	32.09	36.84	43.32
Al ₂ O ₃	31.69	31.44	33.72	31.00	31.77	32.24	28.49	22.09	29.39	29.52	21.11	32.10	32.77
Fe ₂ O ₃ (total)	0.99	0.98	0.81	1.12	2.06	0.77	10.39	23.16	2.71	2.12	31.69	2.83	1.37
MnO	0.05	0.05	-	-	-	-	0.05	0.01	-	-	0.01	-	-
MgO	1.19	1.15	1.24	1.00	1.14	2.40	1.16	4.10	6.22	9.65	1.19	10.15	4.28
CaO	0.28	0.28	0.22	0.09	0.40	0.28	0.26	0.63	0.86	1.00	0.23	0.26	0.27
Na ₂ O	0.05	0.06	0.06	0.03	0.06	0.02	0.06	0.07	0.08	0.08	0.09	0.04	0.03
K ₂ O	9.96	9.77	9.16	8.77	9.78	8.02	7.29	5.66	4.18	1.34	5.60	2.79	6.99
TiO ₂	1.10	1.09	1.52	0.41	1.81	2.32	2.20	2.96	7.22	9.39	0.41	1.72	1.83
P ₂ O ₅	0.25	0.25	0.22	0.18	0.24	0.28	0.27	0.28	0.58	1.18	0.10	0.07	0.10
LOI*	4.30	3.19	4.72	4.76	5.18	5.04	5.86	5.82	5.27	10.47	5.61	10.14	6.56
Total	97.39	95.58	97.76	94.54	98.92	95.88	97.77	97.90	96.93	97.26	98.13	98.75	97.53
S	0.19	0.20	0.28	0.07	0.28	0.19	0.31	0.24	0.29	0.09	0.30	0.31	0.04
U	108	155	46	56	113	105	103	244	79	164	557	66	26
Cu	4	8	<1	4	13	21	2	14	3	4	17	1200	69
Pb	15	25	8	9	20	28	9	110	8	15	100	8	3
Zn	4	15	14	5	6	6	4	180	3	2	9	6	3
Ni	10	51	5	3	64	55	24	250	39	44	34	99	3
Co	4	7	2	<1	19	49	3	90	7	12	15	16	1
Mo	1	1	<1	<1	<1	<1	0.3	4	2	1	<1	2	<1

*LOI: Loss on ignition

ACCESSORY MINERALS AND NEW MINERALS

Detrital accessory minerals are dispersed through barren, unaltered sandstone or are concentrated as thin layers along bedding planes. They include zircon, green tourmaline (commonly surrounded by overgrowths of secondary colourless dravite), and rare apatite and monazite. Anatase and leucosene result from the destabilization of detrital titanomagnetite and ilmenite. Layers of heavy minerals, their main component being specularite, are especially abundant in the basal conglomeratic sandstones.

Accessory minerals, notably zircon and Ti-minerals, are particularly abundant in mineralized zones, where anatase and leucosene are associated with neoformed rutile needles. Some zircons are surrounded by secondary colourless rims of unknown composition. Phosphates are always present; three varieties have been distinguished:

- 1) small colourless crystals of euhedral apatite in clay matrix;
- 2) very small greenish to brownish crystals, locally abundant as aggregates, which appear to correspond to Al-Sr phosphates from the goyazite group; and
- 3) large, elongated (2 to 3mm) crystals, always located at the unconformity in the clay layer below massive

mineralization; they are quite abundant, but are limited to a very narrow host-rock thickness (1 to 50cm); compositionally, they correspond to dahllite (Ca, Mg, Na)₁₀([P,C] O)₁₆(OH,F)₂; their cores are dark coloured, and have a monazite composition. Apatite and goyazite crystals are genetically related to hydrothermal processes, as are dravite needles and aggregates, and are of widespread occurrence in clay-alteration zones. The large phosphate crystals are assumed to be of sedimentary origin (monazite detrital layers) with secondary hydrothermal rims of dahllite composition.

The same accessory minerals are present in the basement, those genetically related to hydrothermal processes being less abundant than in the sandstone.

Siderite, possibly of several generations, is particularly well represented in the clay cap. It occurs as aggregates of euhedral brown crystals, diffuse impregnations, veins and massive layers. Some late dolomite has also been identified. In the western part of the orebody, where argillization processes are not as intensely developed, sandstone and mineralized zones are crosscut by parallel microfractures filled with siderite. The massive brecciated mineralization is, in places, enclosed in a siderite matrix. Such brecciation possibly results from hydraulic fracturing. The siderite veins show microstylolitic structures, corrode quartz grains, and are corroded by clay minerals such as "ferri-kaolinite" and Fe-rich illite. The

development of siderite and hydraulic-fracture argillization, and micro-fracturing, brecciation and corrosion by siderite, together made the rocks highly susceptible to later argillization. Siderite-formation may also have been related to the release of CO_2 caused by oxidation of graphite in the basement. Carbonates such as siderite and calcite are present in the basement, but only to a depth of a few metres below the unconformity; small Al-Sr phosphate crystals are observed to depths of 50 to 60m below the unconformity, as are dravite needles and aggregates. Both phosphates and dravite are associated with altered feldspar, cordierite and garnet, and dravite may also occur with quartz and calcite as late white veinlets.

Accessory minerals are mostly of detrital origin, and Athabasca Group basal sandstones are, for the most part, enriched in heavy minerals. Sedimentary concentration alone does not, however, explain the large proportion of accessory minerals, confirmed by the high values of TiO_2 , P_2O_5 , and ZrO_2 (see Table 3), located in the mineralized zones. Similar enrichment has been observed at the Cluff Lake orebody (Ruhlmann, 1983; Ey, 1984) and at most of the uranium deposits located in the eastern part of the Athabasca Basin (Hoeve and Quirt, 1984). These authors explain the overabundance of accessory minerals by the concentration of refractory minerals through dissolution of quartz grains by hydrothermal fluids. Hoeve and Quirt (1984) proposed that the formation of high-grade orebodies at the unconformity was accompanied by extensive quartz dissolution, residual enrichment of clay and collapse of the overlying sandstones, and that first-stage mineralization shows direct genetic connections with clay-mineral development. At Cigar Lake, massive quartz dissolution, accompanied by the collapse of overlying sandstone, obviously took place, providing a possible explanation for the increased heavy-mineral concentration. The pre-Athabasca basement ridge doubtless locally influenced sedimentary processes and so may have been a factor in the enhanced heavy-mineral concentration.

Ti-minerals readily fix uranium from mineralized solutions, generally forming new U-Ti minerals such as brannerite (Ruhlmann, 1983, Cluff Lake deposit; Ruzicka and Littlejohn, 1982, Rabbit Lake deposit). At Cigar Lake, even where the TiO_2 concentration is very high (up to ten per cent in some samples), only a minor part of the uranium is fixed in the Ti-minerals present among the various complex secondary products.

DISTRIBUTION OF FACIES IN SELECTED DRILL HOLES

A few typical holes have been selected to describe rock-type distribution and the relationship between lithology and mineralization (Fig. 10).

Hole WDG1-110 (line 6 + 00E) is exceptional for its high-grade uranium mineralization (47.6 per cent U) over a short (5m) mineralized interval, its lack of a massive clay cap above the ore zone, the presence of only "indurated" clay in association with pitchblende, its sharp contacts with sandstone, and the absence of oxidation. This part of the deposit is interpreted as being a small pod of primary unoxidized ore in host rock which has not been affected by later tectonic movements, so preserving original characteristics.

Hole WDG1-129 (line 5 + 00W) is located in the western extension of the orebody. Clay alteration and oxidation in fractures are generally weaker than in the "East Zone". Dark grey "indurated" clay alternates with sandstone, argillized sandstone and small amounts of "intermediate" clays.

Hole WDG1-93A (line 10 + 50E) is located at the east end and south of the orebody. As in most of the border holes, its core is strongly fractured. Mineralization is located far from the unconformity, in dark green "indurated" clays which fill fractures in faulted zones and which crosscut sandstone bedding planes. No oxidation is observed, and clay alteration is weak.

Holes WDG1-107 and -117 (line 9 + 00E) are typical holes from the east part of the orebody with thick clay caps above intense mineralization comprised of pitchblende breccia in an "indurated" clay matrix. They are affected by strong oxidation.

Hole WDG1-49A (line 7 + 50E) is located at the south border of the orebody and is crosscut by a major fault. Like the surrounding holes, it is characterized by an abundance of "indurated" clays (silicification and carbonation), strong oxidation, and secondary yellow products.

MINERALIZATION

At Cigar Lake three types of mineralization are found:

- 1) main mineralization at the unconformity,
- 2) perched mineralization, and
- 3) basement mineralization.

MAIN MINERALIZATION

This type of mineralization is mostly located within sandstone, and thus overlies the unconformity. In the "East Zone", where detailed information is available, the orebody is quite homogeneous; it consists of a massive clay zone with low uranium grades surrounding an extremely rich massive ore zone (Fig. 11).

The main mineralization appears to result from hydrothermal processes; its mineral paragenesis is similar to that described for other Athabasca deposits (Hoeve and Quirt, 1984) such as Key Lake (Dahlkamp, 1978), McClean Lake (Wallis and al, 1983) and Cluff Lake (Ruhlmann, 1985).

Metallogenic studies carried out over the past few years by the "Service de Mineralogie" of Cogema indicate that massive mineralization took place during at least three stages.

The first (main) stage of mineralization (Table 2) is characterized by uranium oxide of two habits (radiating and euhedral), development of which was followed by the formation of Ni-Co arsenides and sulpharsenides, and of Ni-Co-Fe sulphides which brecciated the uranium oxide phase. This succession appears to have been commonly produced during mineralizing hydrothermal processes in the Athabasca ore deposits (Ruhlmann, 1983; Hoeve and Quirt, 1984). "Indurated" clays were formed during this first stage. Pitchblende samples have been recently dated (Ruzicka and Lecheminant, 1986; Fig. 12) and provide an age (1300 Ma) very similar to that of the main mineralization of the first event determined in other uranium deposits from this area (Worden et al, 1985; Midwest deposit; Fryer and Taylor, 1983; Collins Bay deposit; Hoeve et al, 1981; Rabbit Lake deposit). Ruzicka

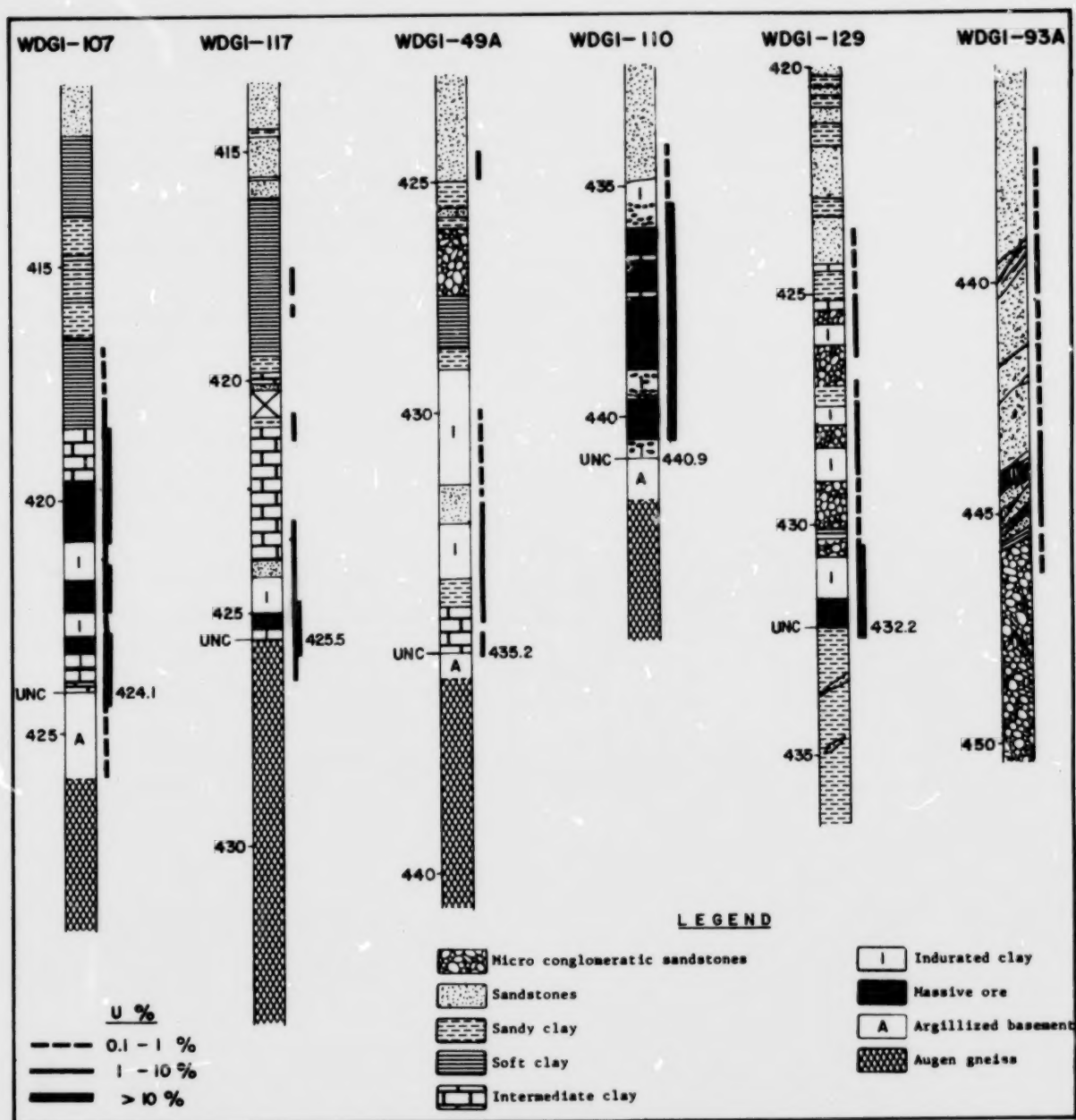


Figure 10. Distribution of facies in the mineralized zones of some typical drill holes (depths in m).

and Lecheminant (1986) noticed that the crystallization of pitchblende was contemporaneous with the thermal event associated with intrusion of the Mackenzie dyke swarms (Fahrig and Wanless, 1963).

The second stage of mineralization is characterized by two pitchblende-bearing parageneses:

- 1) pitchblende associated with secondary Ni-Co arsenides, sulpharsenides, sulphides, and Fe-Cu-rich sulphides, and
- 2) pitchblende associated with Fe-Cu-rich sulphides.

These associations are located in different mineralized structures from those of first-stage mineralization.

The third stage of mineralization appears to have been much later in origin, and is characterized by replacement of pitchblende by Fe-oxides and -hydroxides. This simple pitchblende-hematite association formed during a well defined mineralizing event recognized in most of the Athabasca ore deposits — Key Lake (Trocki et al, 1984), Cluff Lake (Ruhmann, 1983, 1985), and Maurice Bay (Mellinger, 1985), for example. The event occurred 450 to 200 Ma ago.

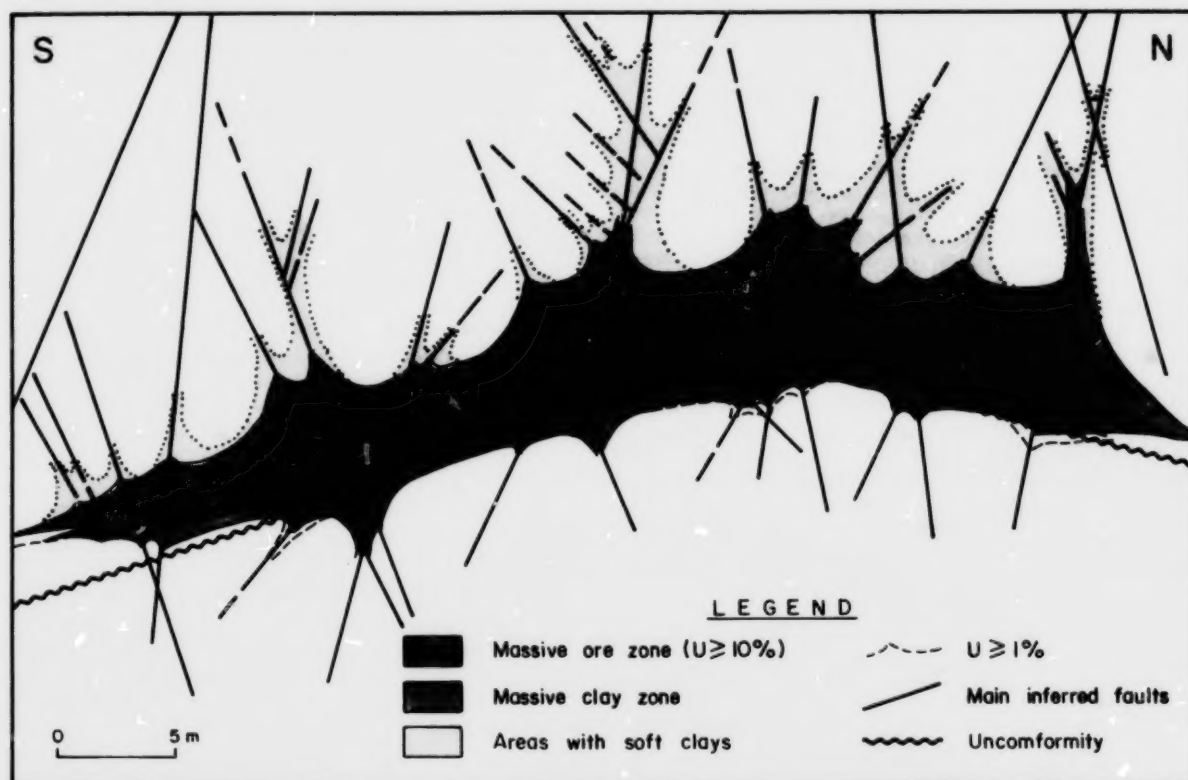


Figure 11. Interpreted cross-section through the Cigar Lake uranium deposit (Line 7 + 75E).

Coffinite is present in all mineralized structures closely associated with Fe-sulphides and "ferri-kaolinite". It apparently postdates an important phase of fracture development which resulted in the brecciation of pitchblende I (defined later under "Basement Mineralization") and of primary arsenides, sulpharsenides and sulphides. The breccia is cemented with coffinite and "ferri-kaolinite". A pyritic mineralization followed, closely associated with coffinite. This coffinite-sulphide association seemingly corresponds to late remobilization of the main mineralization.

PERCHED MINERALIZATION

Perched mineralization describes mineralization located in sandstone over the main orebody, up to 300 m above the sub-Athabasca unconformity. Rare, isolated fractures with low uranium mineralization extend locally to the top of the bedrock. In places, significant metal accumulations are common, but few are of economic interest. Their main characteristics are an intense fracturing of the host rocks, location within the euhedral quartz zone, pale- to dark-grey colour of the sandstone, weakly developed argillization with clay sometimes being totally absent, low ore-grade (only a few samples contain more than one per cent uranium), and a simple, consistent mineralogical association (pitchblende and coffinite with microdisseminated pyrite and marcasite, local bravoite and galena, and — commonly — microscopic hydrocarbon matter). Geochemical analyses indicate preferential mobility of uranium compared to other elements; only very weak enrichment of Ni, Co, Cu, Pb, As and S is observed even where uranium values exceed one per cent.

"Perched mineralization" possibly results from remobilization of unconformity mineralization along steeply-dipping faults. Drill-hole studies show "perched mineralization" to be obviously structurally controlled, with uranium migration along fractures. Around and above the "perched mineralization", uranium, sulphides and organic matter have also migrated, perhaps during late diffusion of U-rich solutions, and are present as dark layers or bands along bedding planes or as irregular dark Liesegang rings. This kind of mineralization has been described from McClean Lake (Wallis et al, 1983), where it is called "Rabbit Ears" type, and is clearly controlled by the porosity of conglomerate layers and by fracture-permeability of the Athabasca Group.

BASEMENT MINERALIZATION

Basement mineralization is of limited importance and comprises rare, thin mineralized intervals. It is generally located near the unconformity and, in most places, appears to have been caused by diffusion of uranium along fractures and faults from high-grade unconformity mineralization. In a few places, however, it seems to be totally disconnected from the main mineralization.

Two types of basement ore have been identified in drill holes:

- 1) "pitchblende vein" - type ore, which shows sharp contacts with surrounding rocks, forms veins 1 to 10 cm thick, follows or crosscuts foliation, and is invaded by veinlets of carbonate; and

- 2) "breccia" - type ore which is comprised of diffusely mineralized zones 0.5 to 3 m thick; it is associated with increasing amounts of graphite, pyrite, carbonates and iron oxides in the host rocks.

The "pitchblende vein" - type uraniferous phases include two forms of uranium oxide and coffinite. Pitchblende I occurs as massive, fractured and cataclastic crystals which grade into coffinite towards their borders. Late recrystallization of prismatic titanium products has taken place at pitchblende margins. Iron oxides and hydroxides, as well as carbonates, invade and replace pitchblende I. Pitchblende II occurs as impregnations in phyllitic clay matrix, commonly along mica cleavages, and is associated with sulphides. These impregnations also grade into coffinite, which was apparently derived from brecciated pitchblende I, and which has been recemented by pitchblende II impregnations. Sulphides are

abundant, are later than pitchblende I, and are intimately associated with pitchblende II along with chalcocopyrite, sphalerite, pyrite, galena, smytheite and rare jordanite.

Late-phase "breccia" - type mineralization is composed of uranium oxide and coffinite with little pitchblende. Sulphides occur as disseminated inclusions, diffuse impregnations, fibrous masses and microveinlets in pitchblende; they suggest several stages of formation. These sulphides include zoned bravoite, melnikovite as fibrous masses, sphalerite as microveinlets, traces of chalcocopyrite, and rare dendritic rammelsbergite. The rock is slightly impregnated with coffinite fixed on the fine sulphide disseminations and on the abundant graphite lamellae. Iron sulphides commonly occur between the graphite lamellae, and may even completely surround them. Pyrite and sphalerite are also trapped in fractures in rutile. Titanium minerals such as rutile are abundant; recrystallized

Table 2. Simplified paragenesis of mineralization.

	Mineralization		Gangue
Stage I	Uranium oxide UO_2		
	- radiating facies (pitchblende)		Fe-rich illite
	- euhedral facies (uraninite)		Mg-rich illite
	----brecciation----		
	Arsenides, sulpharsenides, sulphides		
RAMMELBERGITE	$NiAs_2$	PYRITE	FeS_2
NICCOLITE	NiAs	MARCASITE	FeS_2
GERSDORFFITE	$NiAsS$	BRAVOITE	$(Ni, Co, Fe)S_2$
COBALTITE	$CoAsS$		
GLAUCODOT	$(Co, Fe)AsS$		
	----fracturing----		
Stage II	Uranium oxide UO_2		Siderite
	PITCHBLEND FACIES		"Ferri-kaolinite"
			Sudoite
1. Secondary arsenides, sulpharsenides, sulphides	2. Sulphides		
PYRITE	FeS_2	PYRITE	FeS_2
MARCASITE	FeS_2	MARCASITE	FeS_2
BRAVOITE	$(Ni, Co, Fe)S_2$	(BRAVOITE)	$(Ni, Co, Fe)S_2$
(SMYTHITE)	$(Fe, Ni)_{11}S_{11}$	(SMYTHITE)	$(Fe, Ni)_{11}S_{11}$
CHALCOPYRITE	$(Cu, Fe)S_2$	(CHALCOPYRITE)	$(Cu, Fe)S_2$
(BORNITE)	Cu_3FeS_4	(GALENA)	PbS
(DIGENITE)	Cu_5S_4	(SPHALERITE)	ZnS
(CHALCOCITE)	Cu_2S		
(COVELLITE)	CuS		
GALENA	PbS		
SPHALERITE	ZnS		
(JORDISITE)	MoS_2		
(CLAUSTHALITE)	PbSe		
	----fracturing----		
			Carbonates
Stage III	Uranium oxide and silicate		(calcite)
	PITCHBLEND - COFFINITE		
	Iron oxides and hydroxides		

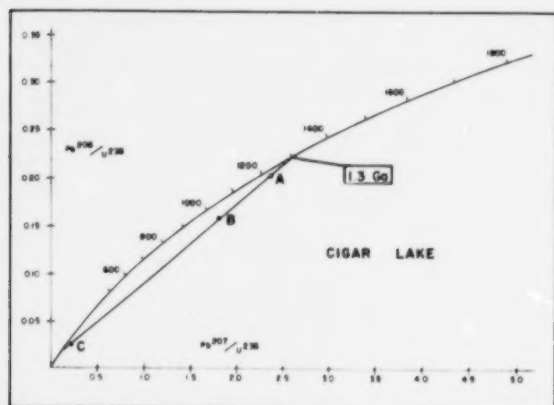


Figure 12. Concordia plot of U-Pb isotope analysis of pitchblende samples from the Cigar Lake uranium deposit (Ruzicka and Lecheminant, 1986).

anatase occurs as acicular crystals, more-or-less bordered by coffinite, in microfissures. Several small masses of isotropic hydrocarbon matter have also been observed. Clay minerals associated with the basement ore are Fe-rich illite, Mg-rich illite and Al-Mg chlorite (sodoite). Geochemical analyses show that MgO-enrichment of the tectonized host rocks (6.5 to 13 per cent MgO) has taken place, and that Zn values are generally higher than those observed in the main mineralization.

GEOCHEMISTRY

Mineralized sections of drill holes have been systematically sampled (50 cm spacing) and analysed for Al₂O₃, K₂O, MgO, U, As, Ni, Co, Cu, Pb, Zn and Mo. In addition, CaO, CO₂, Fe₂O₃ (total), TiO₂, P₂O₅, ZrO₂ and trace elements have been analysed in a few drill holes. The distribution of Al₂O₃, K₂O, MgO, CaO, CO₂, Fe₂O₃ (total), TiO₂, P₂O₅ and ZrO₂ values in a typical mineralized drill hole (WDG1-113) of the "East Zone" is listed in Table 3. The values of the oxides Al₂O₃, K₂O and MgO are related to the rocks' clay contents; of CaO, to their pitchblende contents; of Fe₂O₃, to their siderite and hematite contents; of CO₂, to their siderite contents; of P₂O₅, to their phosphate contents; and of ZrO₂, to their zircon contents. The presence of ilmenite and leucoxene is indicated by TiO₂. Calcite may be present in a few basement samples. Chemical results confirm both the geological observations and the distinction made at the Cigar Lake orebody between three main lithological zones as follows:

- 1) **the clay cap**, characterized by high Al₂O₃ values (up to 32 per cent) and high K₂O values (illite) which are always dominant over MgO (Mg-rich illite $\pm$ chlorite); CO₂ and Fe₂O₃ (total) (siderite and hematite) are well represented; P₂O₅ is generally low, but shows high values (up to 2 per cent) in some drill holes; TiO₂ and ZrO₂ concentrations are dependent on the presence of detrital heavy minerals which may be irregularly distributed;
- 2) **the massive ore zone**: MgO is largely dominant over K₂O in clay-rich sections and is commonly strongly enriched at the unconformity; siderite is generally absent except in some samples where pitchblende is brecciated with veinlets of carbonate; Fe₂O₃ (total) is related to coffinite, "ferri-kaolinite" and hematite

along oxidized faulted zones; a strong correlation exists between Ca and U; TiO₂ values (2 to 5 per cent) are higher than in the clay cap with values above 10 per cent in some drill holes; ZrO₂ values become lower; P₂O₅ shows strong enrichment at the unconformity (basal phosphate levels); and

- 3) **the altered and argillized basement** which is characterized by MgO-enrichment (4 to 12 per cent in some drill holes) related to hydrothermal processes and which extends below the unconformity to a depth of 40-50 m; dravite is common; the main clay mineral is sudoite (Al-Mg chlorite); calcite is commonly present in veins; Fe₂O₃ (total) is strongly depleted, and other oxides such as TiO₂, ZrO₂ and P₂O₅ show normal background values.

Bulk chemical analyses have been carried out on samples from selected areas of the east part of the orebody (Table 4). They average out the characteristics of individual drill holes, and give a general picture of the distribution of the analysed oxides and elements. Variations are quite large for the main components, and areas with siliceous ore (SiO₂ up to 50 per cent) are readily distinguished from areas with argillaceous ore (Al₂O₃ above 20 per cent).

Numerous elements such as As, Cu, Pb, Ni, Co, Zn, and Mo are directly associated with uranium. The average grades are listed in Table 5.

The distribution of eight elements, Pb, Ni, Co, Bi, Cu, Zn, Y and Mo, as a function of uranium is illustrated in Figure 13. In drill hole WDG1-20, the main pitchblende mineralization (zone II) is surrounded by two mineralized areas of lower grade (zone I on top, zone III at the unconformity). Uranium and lead correlate strongly with one another in all three mineralized zones. Lead is mainly radiogenic and is associated with pitchblende, but also occurs as massive galena in some drill holes. In zones I and III, correlations are very high between uranium and Ni, Co and Y, and are high with Cu, Mo and Bi; these elements are strongly depleted in the vicinity of the main mineralization (zone II).

These relationships have been observed in most drill holes in which base metals are located just above or below the massive ore zone. Uranium is the dominant ore metal except in a few places where massive Ni-Co mineralization is present. Zinc (sphalerite) shows an irregular distribution. Other elements which occasionally appear in mineralized samples are: F (up to 2 per cent), Ag (up to 50 ppm) strongly associated with Mo-Bi, Se (up to 800 ppm) associated with Pb-Bi-Fe-Cu in a late cryptocrystalline phase (sulphoselenides), and Th (up to 350 ppm). Locally, antimony and, more rarely, lithium and beryllium show concentrations higher than their respective background values. High vanadium values (1000 to 3000 ppm) occur with sulphides and sulpharsenides. Gold is low (maximum 1250 ppb), usually under the detection limit (5 ppb).

STRUCTURAL INTERPRETATION

Regionally, the structural framework is dominated by large northeast-southwest lineaments well known throughout the Athabasca Basin. In the Cigar Lake area, these lineaments correspond to late major faults associated with brecciation of both basement and sandstone. One possibly forms the western end of the orebody (Tibia Lake Fault, see Figs. 8 and 14).

Table 4. Chemical analyses of bulk samples from various areas of the "East Zone" (all oxides and elements in per cent).

Weight of sample (kg)	32.4	71.5	170.0	53	48.3
SiO ₂	50.75	25.30	42.30	34.31	35.90
Al ₂ O ₃	6.21	19.08	12.00	16.66	16.36
FeO	5.20	10.79	9.09	8.89	18.58
MgO	2.22	1.77	n.a.	2.55	0.98
CaO	0.73	0.29	0.92	0.87	0.41
K ₂ O	0.88	3.14	n.a.	2.18	3.34
TiO ₂	1.45	3.40	2.65	4.85	2.34
P ₂ O ₅	1.40	1.68	0.31	4.04	0.56
S Total	0.96	2.13	1.43	3.16	0.70
CO ₂	2.47	3.12	2.38	1.30	4.75
ZrO ₂	0.103	0.212	0.156	0.235	0.182
U ₂ O ₅	14.27	12.56	12.29	6.78	6.24
Th	0.006	0.013	0.0115	0.020	0.009
Pb	1.82	1.04	1.32	0.60	0.16
V	0.04	0.09	0.095	0.13	0.09
As	1.52	0.81	0.89	4.24	0.18
Ni	1.41	0.75	0.59	2.04	0.16
Co	0.04	0.20	0.14	0.58	0.03
Cu	0.15	0.79	0.74	0.80	0.19
Mo	0.14	0.22	0.12	0.21	0.25
Zn	0.03	0.04	0.04	0.052	0.01

On a more detailed scale, in the East Zone of the orebody, geological observations and neutron-neutron data analysis provide a preliminary tectonic interpretation. Three main sets of fractures have been defined (Fig. 15):

- 1) a 045° to 60° set with predominant NW dip;
- 2) 075° fractures also with a predominant NW dip; and
- 3) 090° to 110° fractures, mostly dipping southwards.

The important 075° set may be Reidel fractures genetically related to a major east-west Hudsonian shear zone. It seems to be associated with the formation of the deposit and divides the orebody into connected lenses. "Perched mineralization" is related to this set. The NE-SW fracture set, also well developed, is of late origin, probably played only a small role in the formation of the Cigar Lake deposit, and is possibly a locus for such phenomena as silicification and late oxidation. The 090° to 110° set appears to be old, restricted to basement rocks only.

Table 5. Average grade (per cent) of various elements associated with uranium in the "East Zone" of the Cigar Lake deposit.

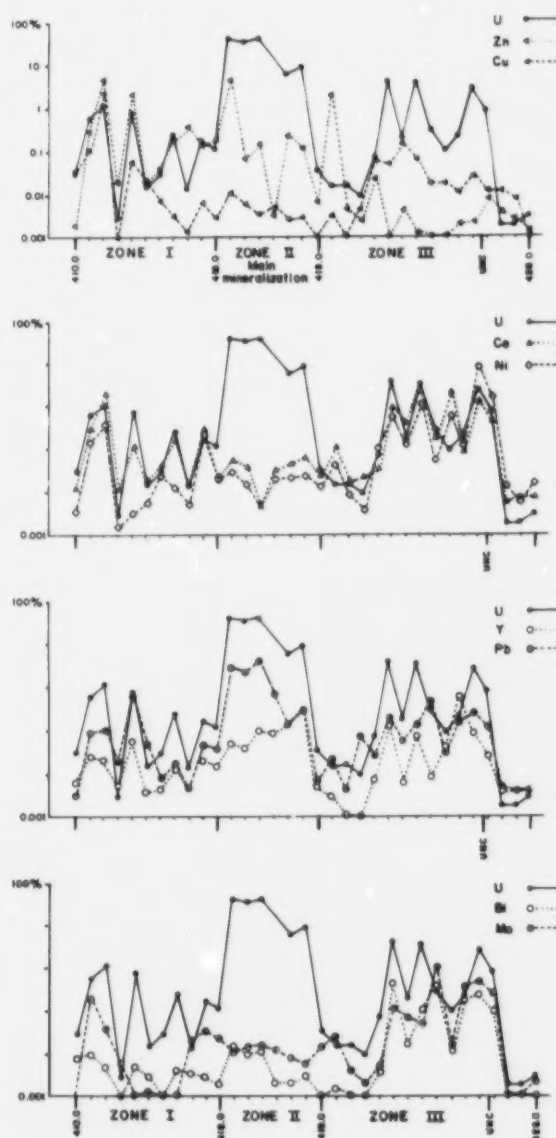
	U	Pb	As	Ni	Co	Cu	Mo	Zn
1*	12.3	1.16	1.67	0.96	0.15	0.7	0.14	0.04
2**	18.5	1.77	2.29	1.38	0.21	0.96	0.21	0.06

* Fouques et al (1986); "East Zone" of the orebody, including geological reserves.

** "East Zone" of the orebody using mining constraints.

Another important set of fractures consists of flat-lying structures (from horizontal to 30° dip), well represented in the 150m of sandstone above the unconformity. This fracturing is concentric, related to the collapse of sandstone after massive quartz dissolution in the vicinity of the orebody. Cross-sections show a cone-shaped, downward-opening structural pattern (Fig. 16). This inverted-funnel-shaped fracture zone is centred over the axis of the unconformity ridge and is continuous over the entire length of the orebody.

The distribution of lithogeochemical haloes, especially for uranium (Fig. 17), is closely dependent on fracture-density. Most uranium values higher than 10 ppm are located within the zone of intense fracturing and clay alteration or along steeply dipping faults which may reach the top of the bedrock.

**Figure 13.** Distribution of Zn, Cu, Co, Ni, Y, Pb, Bi, Mo versus uranium in the mineralized section of drill hole WDGI-20 (Line 3 + 00W).

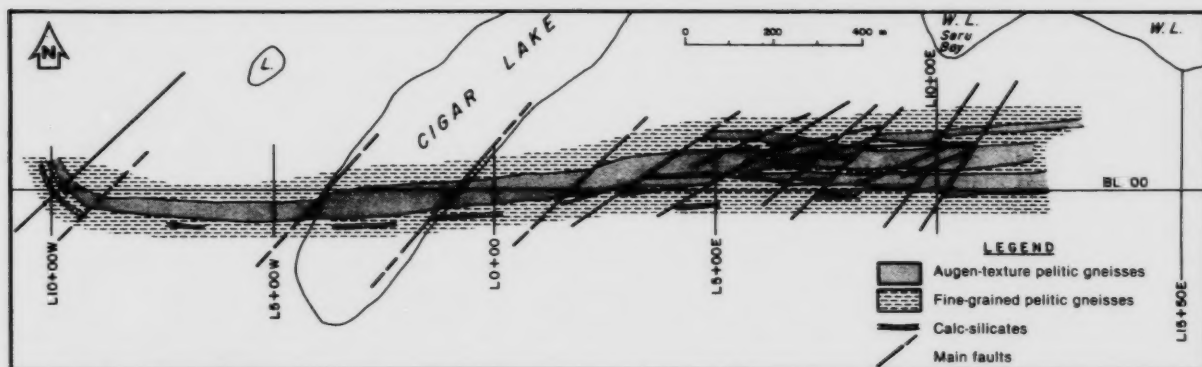


Figure 14. Structural interpretation of the Cigar Lake area, at the unconformity level.

Secondary enrichment takes place as concentric haloes surrounding the fractured areas (4 to 9 ppm zone, 2 to 3 ppm zone) or along preferential levels such as unit D of the Manitou Falls Formation.

Single major structures are rare and difficult to identify. Neutron studies suggest their continuity over distances of only several hundred metres. Structures with "perched mineralization" are probably the most continuous.

CONCLUSIONS

The Cigar Lake ore deposit occurs at the unconformity between Aphebian pelites and Helikian sandstones. It is the world's largest known high-grade uranium deposit, estimated to contain around 150,000 tonnes of uranium metal, with extremely rich mineralization in its eastern part. It presents many similarities to several other unconformity-type deposits of the eastern part of the Athabasca Basin, such as Key Lake, Midwest, McClean Lake and Collins Bay. Its main characteristics are summarized as follows:

- 1) it is a 2.2 km-long, flat, elongated body displaying remarkable continuity;
- 2) it is located at the unconformity between the Aphebian Wollaston Group metasediments and the Helikian Athabasca Group sandstones of the Manitou Falls Formation, at a depth of 410 to 450m; it is devoid of any surficial expression;
- 3) it is probably genetically controlled by an east-west-trending structure of Hudsonian age which corresponds to a graphite- and pyrite-bearing pelitic unit characterized by an augen texture;
- 4) a close relationship exists between the present form of the unconformity surface and the metallic accumulations; the observed basement ridge appears to be a paleorelief feature;
- 5) hydrothermal alteration is well developed, both in basement and sandstone, with alteration arranged in concentric zones around the orebody; its main characteristics are intense fracturing, massive quartz dissolution in sandstone, and extensive development of various types of clay zones enveloping the mineralization;
- 6) ninety-five per cent of total mineralization is concentrated in sandstone at the unconformity; the ore appears to be the result of polyphase hydrothermal processes and consists mainly of uraninite-pitchblende associated with arsenides, sulpharsenides and sulphides; the first (and main) mineralizing event has been dated at 1300 Ma; both parageneses and ages of the ore are similar to those observed in other Athabasca uranium deposits;
- 7) the deposit is polymetallic, and various elements are associated with uranium; these elements include Ni, Co, Cu, Mo, Zn, Pb and As; certain oxides (TiO_2 , ZrO_2 , P_2O_5 and CO_2) may show relatively high values

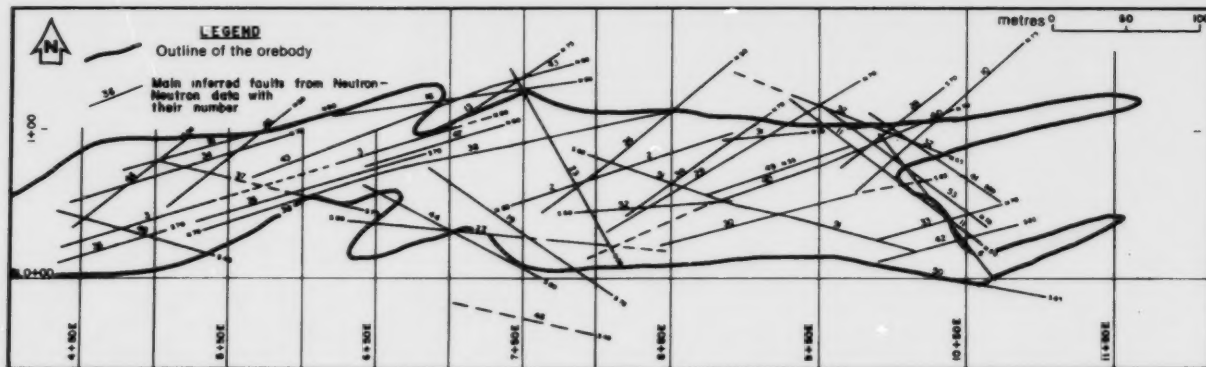


Figure 15. Sandstone fracturing between Lines 4+00E and 11+50E, at 75m above sea level. Fractures are interpreted from neutron-neutron drill-hole logs.

in the clay zones due to the presence there of such heavy minerals as zircon, ilmenite, and phosphates and due to the formation of siderite;

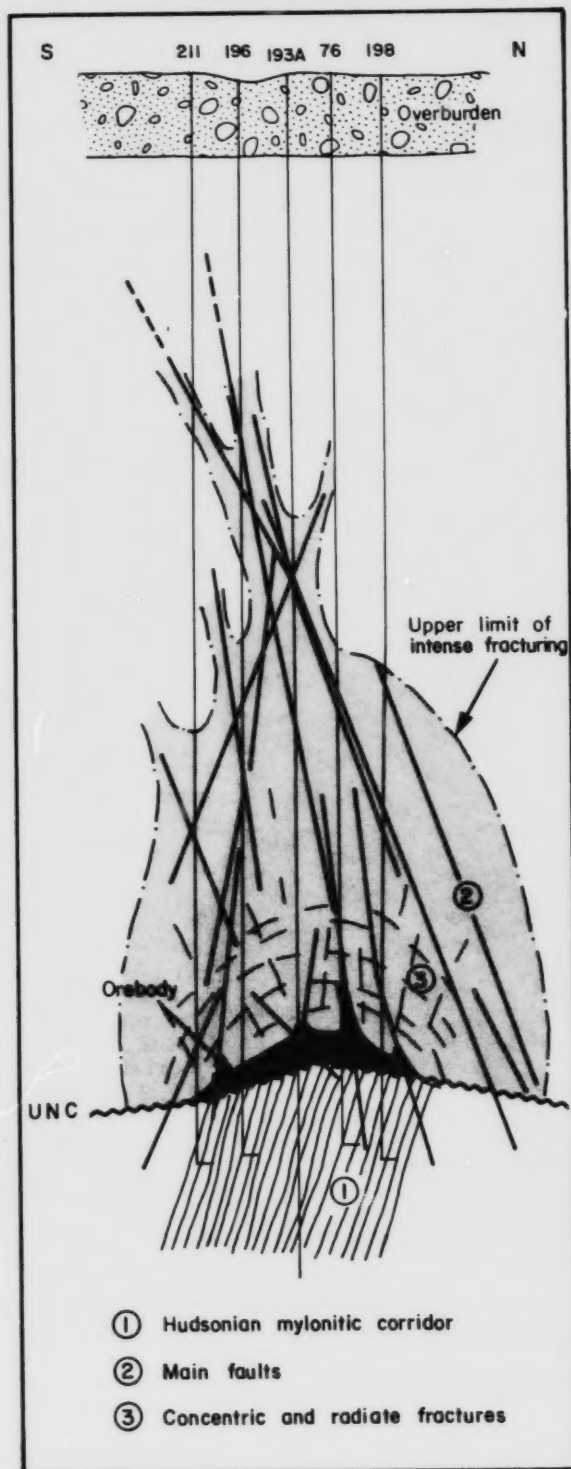


Figure 16. Interpreted fracture pattern surrounding the Cigar Lake uranium deposit (Line 7 + 75E).

- 8) strong fracturing and collapsing of sandstone accompanied the deposition of uranium; dispersion of uranium also occurred in sandstone along steeply-dipping faults to form "perched mineralization" and concentric geochemical haloes.

REFERENCES

- Armstrong, R.L., and P. Ramaekers, 1985, Sr isotopic study of Helikian sediment and diabase dikes in the Athabasca Basin, Northern Saskatchewan: *Canadian Journal of Earth Sciences*, v. 22, p. 399-407.
- Ayres, D.E., E.M. Wray, J. Farstad, and H. Ibrahim, 1983, Geology of the Midwest uranium deposit, in E.M. Cameron, ed., *Uranium Exploration in Athabasca Basin, Saskatchewan*, Canada: Geological Survey of Canada Paper 82-11, p. 33-40.
- Bell, K., and R. Macdonald, 1982, Geochronological calibration of the Precambrian Shield in Saskatchewan, in R. Macdonald, T.I.I. Sibbald, D.F. Paterson, P. Gulio and J.V. Buller, eds., *Summary of Investigations 1982*, Saskatchewan Geological Survey: Saskatchewan Energy and Mines Miscellaneous Report 82-4, p. 17-22.
- Bruneton, P., and P. Caumartin, 1985, Le Gisement d'uranium de Cigar Lake (Saskatchewan, Canada). Contribution a la comprehension des mecanismes de formation des gisements de l'Athabasca, in *Concentration Mechanisms of Uranium in Geological Environment*, Extended Abstracts: International Meeting, Nancy, October 2nd to 5th, 1985, p. 211-214.
- Dahlkamp, E.J., 1978, Geological appraisal of the Key Lake U-Ni deposits, Northern Saskatchewan: *Economic Geology*, v. 73, p. 1430-1449.
- Ey, F., 1984, Un exemple de gisement d'uranium sous discordance: Les mineralisations Proterozoiques de Cluff Lake, Saskatchewan, Canada: These 3eme cycle, Institut de Geologie, University of Strasbourg, 171p.
- Fahrig, W.F., and R.K. Wanless, 1963, Age and significance of diabase dyke swarms of the Canadian Shield: *Nature*, v. 200, p. 934-937.
- Fouques, J.P., and J.E. Tosney, 1985, The Cigar Lake Project — Concepts for mining high grade unconformity uranium ores, Athabasca Basin: *Atomic Industrial Forum*, September 29th, 1985, Santa Fe, U.S.A.
- Fouques, J.P., M. Fowler, H.D. Knipping, and K. Schimann, 1986, The Cigar Lake uranium deposit: Discovery and general characteristics, in E.L. Evans, ed., *Uranium Deposits of Canada: Canadian Institute of Mining and Metallurgy Special Volume 33*, p. 218-229.
- Fryer, B.J., and R.P. Taylor, 1984, Sm-Nd direct dating of the Collins Bay hydrothermal uranium deposit, Saskatchewan: *Geology*, v. 12, p. 479-482.

Hoeve, J., and T.I.I. Sibbald, 1978, On the origin of Rabbit Lake and other unconformity-type uranium deposits in

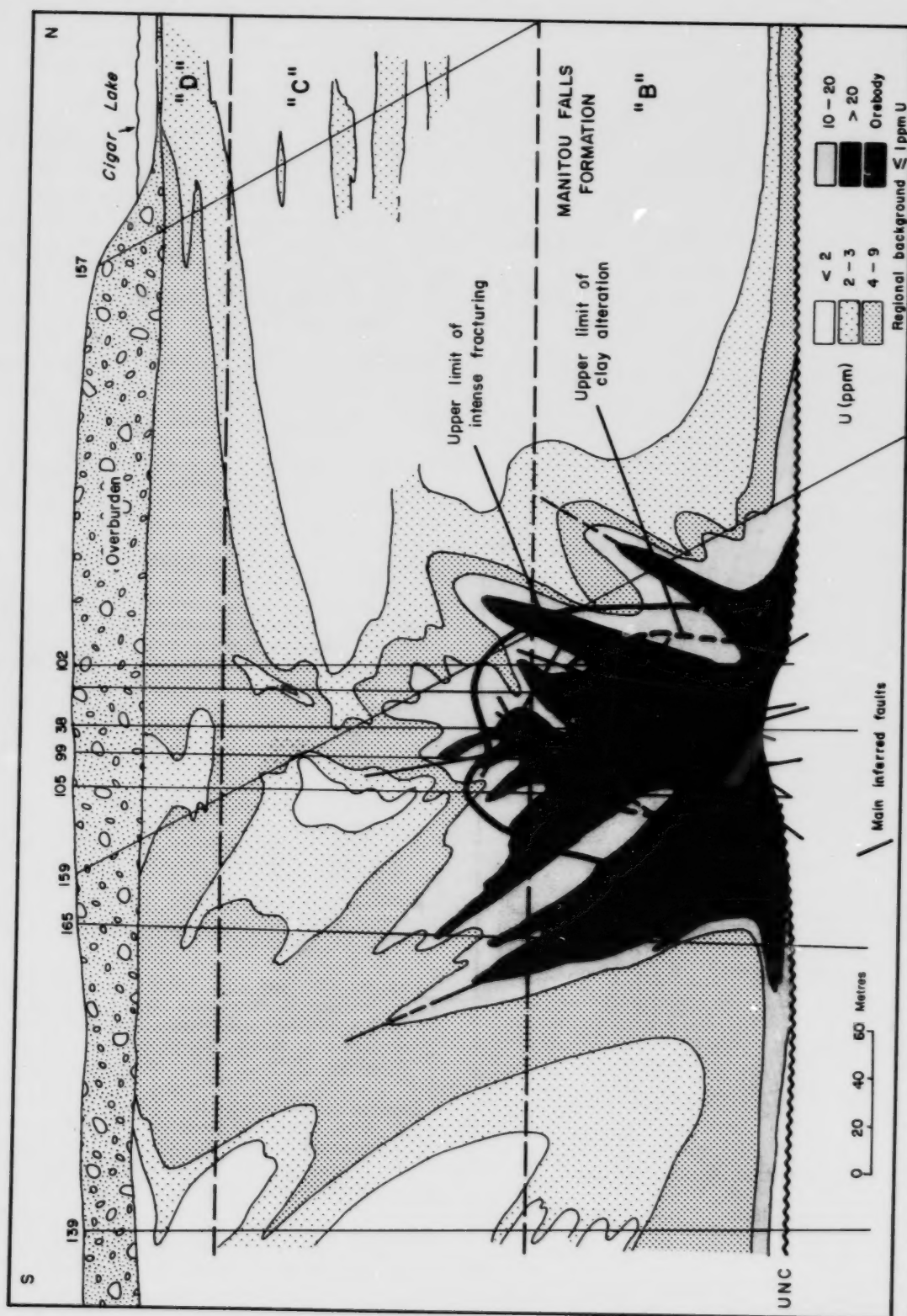


Figure 17. Uranium distribution in the sandstones around the Cigar Lake ore deposit (Line 4 + 50E).

- Northern Saskatchewan: Economic Geology, v. 73, p. 1450-1473.
- Hoeve, J., G.L. Cumming, H. Baadsgaard, and R.D. Morton, 1981, Geochronology of uranium metallogenesis in Saskatchewan: Canadian Institute of Mining and Metallurgy Geology Division, Uranium Symposium and Field Tours (Abstracts).
- Hoeve, J., and D. Quirt, 1984, Uranium mineralization and host rock alteration in relation to clay mineral diagenesis and evolution of the Middle Proterozoic Athabasca Basin, Northern Saskatchewan, Canada: Saskatchewan Research Council Technical Report No. 187.
- Ibrahim, H.J., and H.F. Woo, 1985, Geochemical and mineralogical alteration at the Midwest uranium-nickel deposit, in T.I.I. Sibbald and W. Petruk, eds., Geology of Uranium Deposits: Canadian Institute of Mining and Metallurgy Geology Division Special Volume 32, 73-84.
- Laine, R., D. Alonso, and M. Svab, 1985, The Carswell Structure uranium deposits, Saskatchewan: Geological Association of Canada Special Paper 29, 230 p.
- Lewry, J.F., and T.I.I. Sibbald, 1977, Variation in lithology and tectonic metamorphic relationship in the Precambrian basement of Northern Saskatchewan: Canadian Journal of Earth Sciences, v. 14, p. 1453-1467.
- Macdonald, C.C., 1985, Mineralogy and geochemistry of the sub-Athabasca regolith near Wollaston Lake, in T.I.I. Sibbald and W. Petruk, eds., Geology of Uranium Deposits: Canadian Institute of Mining and Metallurgy Special Volume 32, p. 155-158.
- Mellinger, M., 1985, The Maurice Bay uranium deposit (Saskatchewan): Geology, host-rock alteration and genesis, in T.I.I. Sibbald and W. Petruk, eds., Geology of Uranium Deposits: Canadian Institute of Mining and Metallurgy Geology Division Special Volume 32, p. 140-150.
- Ramaekers, P., 1981, Geochemistry of the Athabasca Sandstone; implications for uranium genesis: Canadian Institute of Mining and Metallurgy Geology Division, Uranium Symposium and Field Tours (Abstracts).
- Ramaekers, P., 1983, Geology of the Athabasca Group, NEA/IAEA Athabasca Basin test area, in E.M. Cameron, ed., Uranium Exploration in Athabasca Basin, Saskatchewan, Canada: Geological Survey of Canada Paper 82-11, p. 15-25.
- Ramaekers, P., 1986, Geology of the Manitou Falls Formation, Waterbury Lake area: Cogema Canada Limited internal report.
- Ray, G.E., 1975, Foster Lake (NE) and Geikie River (SE) areas, in J.E. Christopher and R. Macdonald, eds., Summary of Investigations 1975, Saskatchewan Geological Survey: Saskatchewan Department of Mineral Resources, Regina, p. 13-18.
- Ruhlmann, F., 1983, Caractéristiques mineralogiques des principales occurrences uranifères de l'anneau de Carswell (Cluff Lake, Athabasca), in Les gisements d'uranium liés spatialement aux discordances: Memoire CREGU no. 1, p. 115-122.
- Ruhlmann, F., 1985, Mineralogy and metallogeny of uraniferous occurrences in the Carswell Structure, in R. Laine, D. Alonso and M. Svab, eds., The Carswell Structure Uranium Deposits, Saskatchewan: Geological Association of Canada Special Paper 29, p. 105-120.
- Ruzicka, V., and A.L. Littlejohn, 1982, Notes on mineralogy of various types of uranium deposits and genetic implications, in Current Research, Part A, Geological Survey of Canada Paper 82-1A, p. 341-349.
- Ruzicka, V., and G.M. Lecheminant, 1986, Developments in uranium geology in Canada, 1985, in Current Research, Part A, Geological Survey of Canada Paper 86-1A, p. 531-540.
- Sibbald, T.I.I., 1983, Geology of the crystalline basement, NEA/IAEA Athabasca test area, in E.M. Cameron, ed., Uranium Exploration in Athabasca Basin, Saskatchewan, Canada: Geological Survey of Canada Paper 82-11, p. 1-14.
- Trocki, L.K., D.B. Curtis, A.J. Gancarz, and J.C. Banar, 1984, Ages of major uranium mineralization and lead loss in the Key Lake uranium deposit, Northern Saskatchewan, Canada: Economic Geology v. 79, p. 1378-1386.
- Wallis, R.H., N. Saracoglu, J.J. Brummer, and J.P. Golightly, 1983, Geology of the McClean uranium deposits, in E.M. Cameron, ed., Uranium Exploration in Athabasca Basin, Saskatchewan, Canada: Geological Survey of Canada Paper 82-11, p. 71-110.
- Worden, J.M., G.L. Cumming, and H. Baadsgaard, 1985, Geochronology of host rocks and mineralization of the Midwest uranium deposit, Northern Saskatchewan, in T.I.I. Sibbald and W. Petruk, eds., Geology of Uranium Deposits: Canadian Institute of Mining and Metallurgy Special Volume 32, p. 67-72.

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THE GAERTNER URANIUM OREBODY AT KEY LAKE (NORTHERN SASKATCHEWAN, CANADA) AFTER THREE YEARS OF MINING: AN UPDATE OF THE GEOLOGY

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ABSTRACT

The Gaertner and Deilmann uranium orebodies at Key Lake are located at the southeastern edge of the Athabasca Basin, approximately 240 km north of La Ronge, Saskatchewan. The deposits were discovered in 1975 and 1976 respectively by Uranerz Exploration and Mining Limited (U.E.M.) as the operator of a joint venture with Saskatchewan Mining Development Corporation (S.M.D.C.) and Inexco Oil Ltd. The latter subsequently sold its share to Eldor Resources Limited and S.M.D.C. Reserves amount to approximately 3.75 million tonnes of ore with an average grade of 2.4 per cent U_3O_8 . In 1979, Key Lake Mining Corporation was founded and instituted as the operator of the mining and milling project. Production started in October 1983. Key Lake Mining Corporation is at present the world's largest uranium producer with an annual production of about 12 million pounds of U_3O_8 .

In January 1983, bedrock-hosted ore was uncovered for the first time — at the contact with esker material. Mining faces across the ore zone subsequently provided the opportunity for detailed examination of host rock alteration, ore distribution and ore mineralogy.

The following geological features recognized on mining faces enhance the interpretation of exploration and development drill core:

- 1) The ore is located along the intersection of the Aphebian-Helikian unconformity with a subvertical strike fault which was repeatedly reactivated, affecting the ore and its alteration halo.
- 2) Hydrothermal alteration: illitization and kaolinitization overprint the pre-Helikian paleoweathering profile; also silicification, development of dravite veinlets, and carbonate formation is evident in gneisses located adjacent to the ore zone. In sedimentary rocks of the Athabasca Group, an illite halo a few hundred metres in width across the strike of the orebody is overprinted by a narrow kaolinite halo of varying width. This kaolinitization is most strongly developed in the centre of the ore zone, where quartz was replaced by kaolinite along joints and fractures, resulting in fault conglomerates similar to the "zone a boules", a term used at the D orebody, Cluff Lake, Saskatchewan. The kaolinitization also resulted in corrosion and redistribution of ore. The precipitation of pyrite on joints, the crystallization of euhedral quartz on dissolution fractures, the formation of voids and microbrecciation are common in a transitional overlapping zone between the wider illite and the narrower kaolinite haloes. Dravite, siderite and illite of low crystallinity are the last-formed minerals in the ore zone.
- 3) High-grade ore exceeding ten per cent U_3O_8 is found as repeatedly fractured and healed uraninite - nickelsulpharsenide - pitchblende assemblages which occur as fragments of veins and/or as patches in sandstone breccia, and as clay-hosted aggregates. Anisotropic uraninite, believed to represent one of the oldest mineralization phases (1350 Ma to 1250 Ma), is found in both the Athabasca Group rocks and Aphebian basement rocks.

Based on field observations as well as petrographic and mineralogical examinations, the conclusion is reached that uraninite was initially deposited in fractures located in Athabasca Group sedimentary rocks above graphitic gneiss. Repeated fracturing of ore veins provided space for the precipitation of polymetallic mineralization until 900 Ma. The basin-wide kaolinitization event around 300 Ma resulted in intensive clay alteration along the centre of the structure and in the redistribution of the ore metals. Faulting (at about 100 Ma?) affected the argillitized deposit.

INTRODUCTION

The Key Lake uranium deposit is located at the southeastern rim of the Athabasca Basin, approximately 240 km north of La Ronge, Saskatchewan (Fig. 1). A provincial all-weather road provides year-round access.

The deposit consists of two parts:

- 1) the Gaertner orebody, discovered by Uranerz Exploration and Mining Limited (U.E.M.), operator of a joint venture which also involved Saskatchewan Mining Development Corporation (S.M.D.C.) and Inexco Oil Ltd., in 1975 after five years of intensive exploration efforts that entailed radiometric prospecting, sampling of lake bottom sediments, studies of the surficial geology, geophysical surveys and diamond drilling; and
- 2) the Deilmann orebody, which was discovered along strike from the Gaertner orebody in 1976.

Detailed accounts of the exploration history are provided by Tan (1977), Kirchner and Tan (1977) and Gatzweiler et al (1980).

The Gaertner orebody has a length of approximately 800 m. The width varies from 10 to 40 m. The mineralization reaches a maximum vertical extent of about 50 m. The ore is not subcropping except for a small area where it is overlain directly by unconsolidated glacial sediments.

The Deilmann orebody is larger than the Gaertner, and extends over a length of approximately 900 m. It is generally about 40 m thick and 30 to 50 m wide. It is covered by Athabasca Group sediments and glacial overburden which, together, have an average thickness of close to 90 m. Ore shoots extend to a depth of about 200 m below the surface.

The two orebodies contain a combined total of approximately 3.75 million tonnes of ore with an average grade of 2.4 per cent U_3O_8 (Young et al, 1982).

The mine and mill complex are located within a mineral lease covering approximately 8040 ha. They are operated by the Key Lake Mining Corporation (K.L.M.C.) on behalf of S.M.D.C., U.E.M., and Eldor Resources Limited which financially share the Key Lake joint venture 50, 33.3 and 16.7 per cent respectively.

The removal of overburden above the Gaertner orebody started late in 1981. The overburden consists of lake-bottom sediments, muskeg, and glacial outwash sand which is underlain by till and esker material.

In January 1983, bedrock-hosted ore was uncovered for the first time. Mining faces across the ore zone subsequently provided the opportunity for detailed examination of host-rock alteration, ore distribution and ore mineralogy.

Production of yellowcake started in October 1983. Key Lake Mining Corporation is at present the world's largest uranium producer with an annual production of about 12 million pounds of U_3O_8 .

GENERAL GEOLOGY

CRYSTALLINE BASEMENT

The Shield in northern Saskatchewan is part of the Churchill Structural Province (Stockwell, 1970). By using structural and metamorphic features, several domains have been distinguished by Lewry et al (1978). The Wollaston Domain is the most prominent in terms of uranium occurrences (Fig. 1). The Key Lake deposit is located near its western margin at the southeastern rim of the Athabasca Basin.

In the Key Lake area (Fig. 2), the basement rocks of the Wollaston Domain consist of red or grey granitoid gneisses (hornblende-biotite-quartz-feldspar gneisses), presumably of Archean age, overlain by a series of Aphebian cordierite-biotite-quartz-feldspar gneisses. Based on grain size, presence of augen texture, and content of anatectic layers, several sub-units have been distinguished within the Aphebian sequence by Agnerian and Kwan (1983). The gneisses carry as accessory minerals sillimanite, apatite, zircon, allanite, pyrite, and chalcophyllite. Graphite is present either in disseminated form or in less-than-millimetre-thick, discontinuous layers draped around porphyroblasts. The latter type is generally found in well defined horizons. Garnets are abundant in rock units ranging in thickness from a few centimetres to several metres. Less abundant rock types within the development-drilling area of the orebodies are amphibolites, calc-silicates, quartzites, and mylonites.

The granitoid basement and the overlying Aphebian sediments were deformed and metamorphosed during the Hudsonian Orogeny (1800 Ma). Several phases of folding resulted in the formation of elongated, northeasterly trending, granitoid-

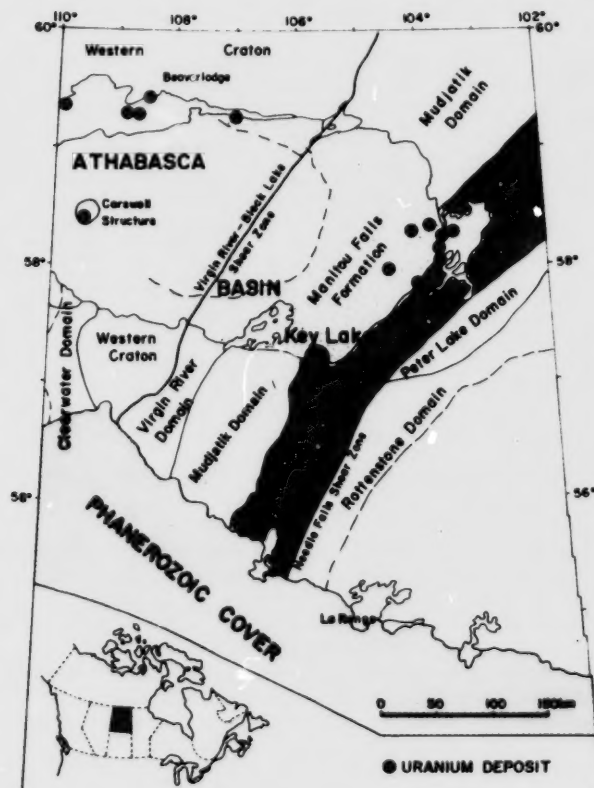


Figure 1. General geological map of Northern Saskatchewan. Modified after Lewry and Sibbald (1978).

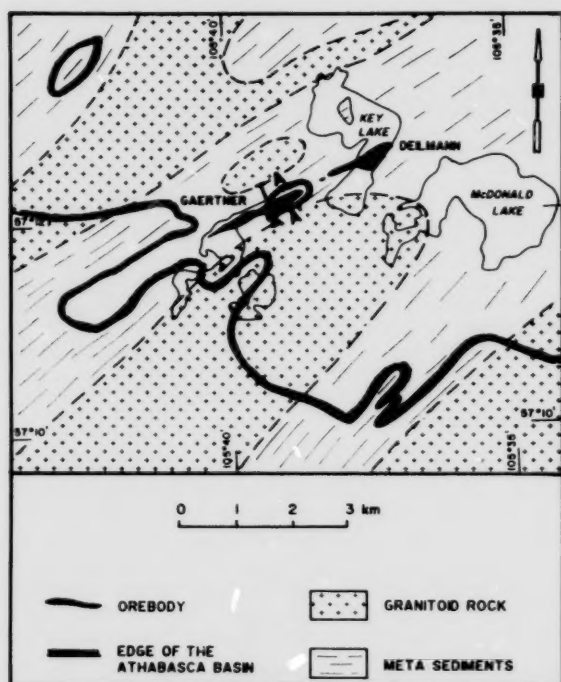


Figure 2. Generalized geological map of the Key Lake mineral lease.

cored domes (Money, 1968; Money et al, 1970). The Key Lake deposit is located on the northwestern flank of such a structure.

The metamorphic grade ranges from Abukuma-type upper amphibolite facies (Winkler, 1967) to granulite facies. Augen texture, due to garnets, cordierite and feldspar crystalloblasts, is present mostly in graphitic portions of the Apebian sequence. Stratiform anatectic segregations form more than ten per cent of the rock volume. They are represented by orthoclase-plagioclase-quartz pegmatoids which, in places, carry graphite and apatite. Crosscutting pegmatoids are rare. Chlorite veinlets, cummingtonite replacement of common hornblende and biotite, and biotite with exsolution of muscovite are all indications of retrograde metamorphism (Von Pechmann, 1985).

The Hudsonian Orogeny was followed by a phase of weathering and peneplanation. The paleoweathering profile is overprinted by a post-Athabasca diagenetic-hydrothermal process (Hoeve and Sibbald, 1978; Macdonald, 1980) which extends into the metamorphic basement in places to a depth exceeding 100 m. These alteration profiles have characteristics which depend on the original rock composition (Macdonald, 1980): in biotite-quartz-feldspar gneisses, the profile immediately underneath the unconformity consists of a bleached zone characterized by kaolinization and quartz removal. The bleaching overprints an illitic hematite zone in which hematite has been formed along cleavage planes of illitized biotite. Chlorite (ditrioctahedral sudoite according to Hoeve, 1982) is also present in subordinate amounts.

The hematite zone is separated from an underlying green zone composed mainly of illite and trioctahedral chlorite (Hoeve, 1982) by a transitional red-green zone consisting of alternating bands of illitic hematite and illite-with-chlorite.

ATHABASCA GROUP

The weathering was followed by the deposition of the sediments of the Middle Proterozoic Athabasca Group. In the Key Lake area, the Athabasca Group is represented by the lower Manitou Falls Formation (Ramaekers, 1979) which comprises quartzites with a few conglomeratic layers. Pebbly beds are increasingly sparse towards the top of the Manitou Falls Formation. Clasts are invariably quartzitic in composition except in the basal conglomerate, where a few lithic pebbles and boulders have been observed.

Quartz is the main detrital mineral. Biotite and rock fragments are present in minor quantities. Volcanic material observed in other formations of the Athabasca Group are absent. Heavy mineral layers consist of tourmaline, magnetite and zircon. The roundness and degree of sorting of the detrital components vary. Interstitial space is generally filled by syntaxial quartz, clay minerals and, rarely, carbonates. The widespread purple colouration is caused by specular hematite.

Hematite may be of detrital origin (Ramaekers and Dunn, 1977), or may have formed as coatings on detrital quartz grains during early diagenesis, before silicification (Hoeve and Quirt, 1984). It occurs also as a coating of rhythmic quartz overgrowths and as an overprint in the interstitial clay matrix, features which point to a late-diagenetic or alteration-related redistribution.

Clay minerals in the matrix of the Manitou Falls Formation consist of approximately equal amounts of illite and kaolinite. Kaolinite, however, is the predominant clay mineral in siltstone layers and in structural zones (Hoeve et al, 1981).

Detailed petrographic and clay mineralogical descriptions of the Athabasca Group are given in Ramaekers and Dunn (1977), Ramaekers (1979, 1980, 1981) and Hoeve and Quirt (1984).

The Manitou Falls Formation is interpreted as being a fluvial deposit of red-bed character which was laid down by braided streams originating in the east (Ramaekers and Dunn, 1977).

Diabase dykes and sills were intruded into the Athabasca Group during the time period from 1350 to 1000 Ma (Bell, 1981; Armstrong and Ramaekers, 1985).

OVERBURDEN

Pleistocene sandy tills, eskers and glacial outwash sand extensively cover the bedrock.

GEOLOGY OF THE GAERTNER OREBODY

STRATIGRAPHY

The principal lithological units in the Gaertner pit are shown on a simplified section across the orebody (Fig. 3).

Basement

The oldest rocks within the limits of the Gaertner open pit are Apebian grey-green migmatitic biotite-quartz-feldspar gneisses. Coarse-grained, anatectic, stratiform layers of felsic material are common. Sillimanite- and cordierite-bearing, graphite-rich gneisses are present in two units: the "main graphite" and the "upper graphite". The "main graphite" is located adjacent to the strongly clay-altered ore zone. It is heavily sheared and contains up to 30 per cent graphite and up to 3 per cent pyrite in fist-sized samples. It extends up to the unconformity, whereas the "upper graphite" — which

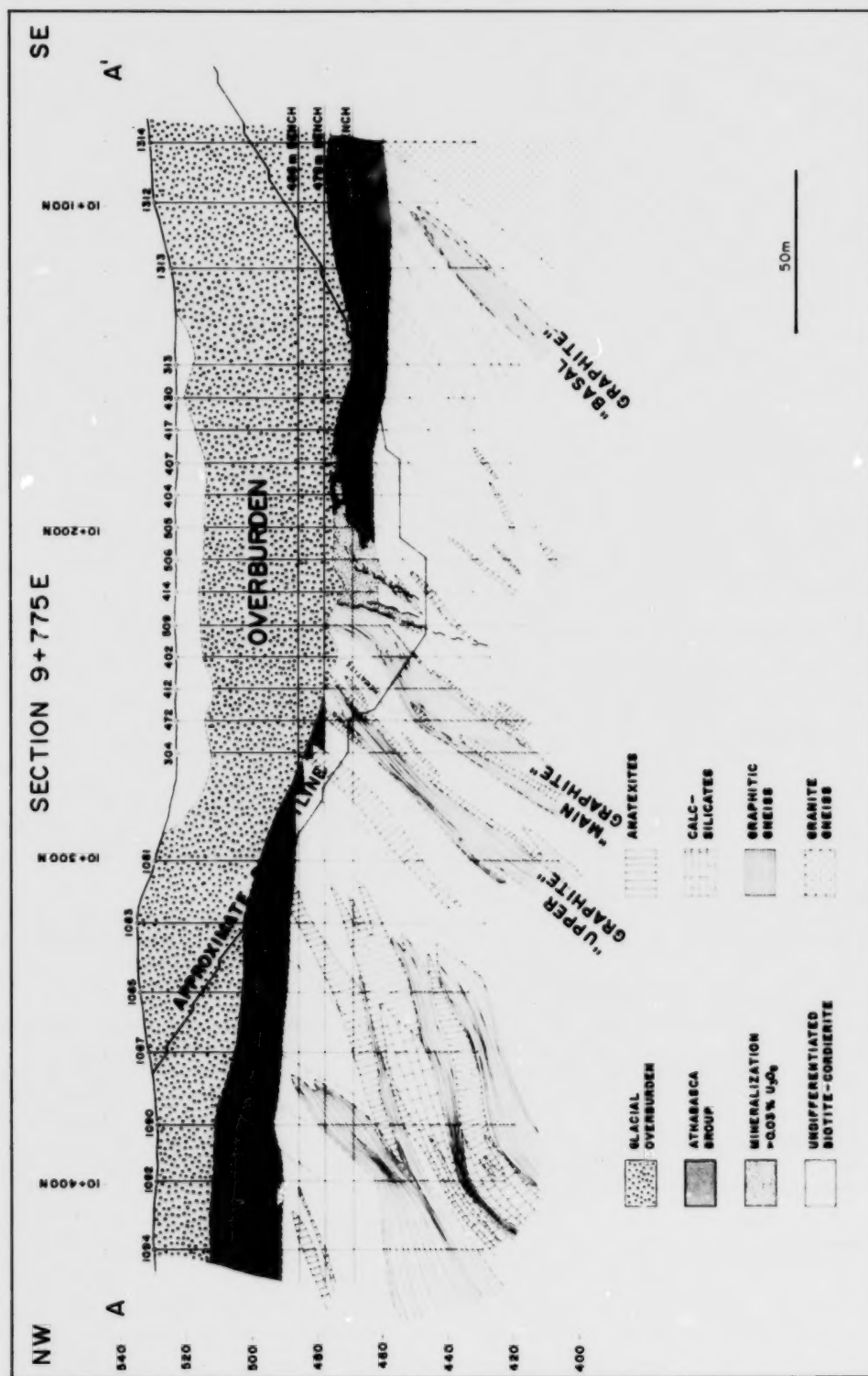


Figure 3. Simplified cross-section (A-A' on Fig. 2), showing the main lithological units in the area of the Gaertner pit.

contains less graphite — appears to terminate 1 to 5 m below the unconformity. In both the main and upper graphitic gneisses, the graphite flakes are frayed due to impregnation by quartz or clay minerals.

An approximately 20-m-thick series of migmatitic biotite gneisses separates the main from the upper graphitic gneiss. These biotite gneisses are overprinted by purple hematization which appears to represent relict paleoweathering of the red-green zone.

Athabasca Group

The basement gneisses are unconformably overlain by sedimentary rocks of the Athabasca Group.

In the central part of the Gaertner pit, the Athabasca sequence begins with a 10- to 12-m-thick unit made up of conglomeratic sandstones which contain about 30 per cent gravel beds. (Ramaekers, 1985). A basal quartz-pebble conglomerate up to 20 cm thick is generally present.

This lowermost unit is overlain by approximately 12 m of sandstone with less than 5 per cent conglomerate content.

Discontinuous siltstone layers and lenses are present in the sequence above the basal conglomerate.

Paleocurrent measurements indicate a direction of transport from 108° (Ramaekers, 1985).

The colour of the Athabasca Group is generally pale grey. Purple hematite (specularite), which suggests little alteration of the host rock has taken place, is present only in the southwestern portion of the Gaertner pit either as stratiform layers or as motley patches.

Overburden

Basal till, esker material, glacial outwash sand and lacustrine sediments cover the Gaertner orebody and its host rocks.

The basal till consists mainly of angular to subrounded grey sandstone fragments hosted in a sandy matrix. The clay fraction amounts to less than six per cent (Fortuna, 1983). Fragments of U-Ni ore are present in the down-ice direction from the contact with the orebody.

Esker material is found in south- to southwest-trending ridges that extend to bedrock. It consists of subrounded to well rounded grey or hematitic sandstone boulders in a sandy matrix. Basement-derived boulders are present in subordinate quantities. Pitchblende cobbles are found in a down-stream direction from the contact with ore.

Well sorted, cross-bedded glacial-outwash sand covers the other types of glacial overburden above an erosional surface. Locally it incorporates underlying glacial material at its base.

Staining by limonite and manganese is ubiquitous.

STRUCTURES

The ore is located along the intersection of the Aphebian — Helikian unconformity with a northwest-dipping strike fault which can be traced over a length of 7 to 8 km. Tan (in Dahlkamp, 1978) has shown that rocks on the southeastern side of this fault have been downthrown approximately 30 m (Fig. 4).

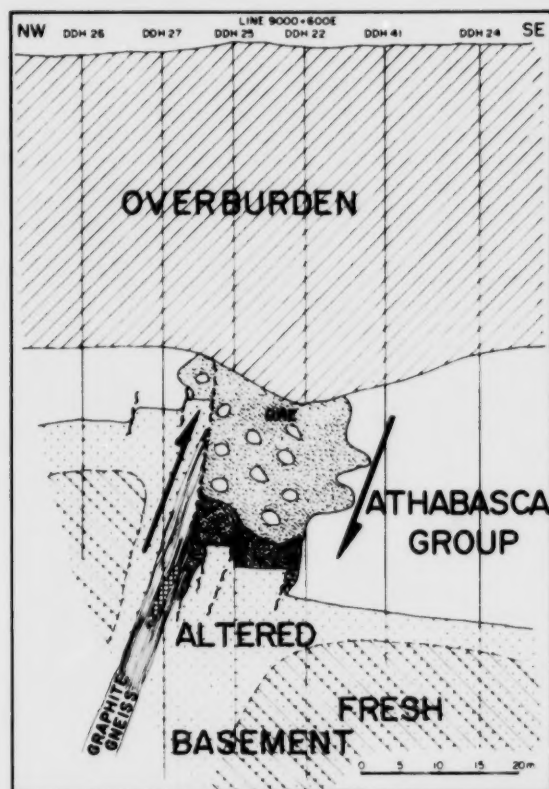


Figure 4. Simplified geological cross-section of the Gaertner orebody. Modified after Dahlkamp (1978).

In the Gaertner pit, the following features have been observed:

Basement

In the basement rocks, three phases of deformation have been recognized:

- 1) **Mylonitization** — a well preserved stratiform quartz mylonite up to 2 m thick is present. It predates the deposition of the Athabasca Group, and fragments of mylonite were deposited in the basal conglomerate of the Manitou Falls Formation in the immediate vicinity of the subcrop. Other mylonites intersected by drilling have not yet been encountered in the Gaertner pit.
- 2) **Folding** — folds with axes parallel to the dip of the basement have amplitudes of one to two metres and wavelengths of up to ten metres (Ramaekers, 1985). In places, the gneisses are folded about subhorizontal axes which trend parallel to the Key Lake structure. These folds have a wide range of amplitudes and wavelengths (1 cm to 10 m) and are disharmonic. This suggests differential plastic movement within the gneisses.
- 3) **Brecciation** — the folding is followed by at least two brittle-deformation events which postdate the mineralization. The first of these was accompanied by hematization and/or emplacement of quartz and dravite veinlets which cut across the folding. It provided channelways which enabled post-ore clay



Figure 5. A) Low-grade, in most cases barren, folded graphitic gneiss (right) of the uplifted block in fault contact with sandstone-hosted, high-grade ore of the downthrown block (left). The folds in the graphitic gneiss are truncated. Height of mining face approximately 8 m; 470 m bench, looking west.

B) At higher levels, non-graphitic gneisses are locally in fault contact with the high-grade ore zone. Height approximately 4 m; 478 m bench, looking southwest.

alteration and resultant partial remobilization of ore to take place. The second event followed this alteration phase, and is characterized by brecciation along steeply dipping strike faults that locally truncate both the main graphitic gneiss and folds in the graphitic and non-graphitic gneisses (Fig. 5).

In the Key Lake structural zone, the fault with the largest vertical throw is associated with the second event of brittle deformation. Little or no alteration seems to be associated with this fault.

The contact between the basement of the uplifted northwestern block and the mineralized zone is sharp in terms of uranium grades and alteration.

Athabasca Group

Within the pit limits, structures affecting the Athabasca Group are characterized by intensive brecciation partially accompanied by strong clay alteration and by dravite- and quartz-veining.

The Key Lake structural zone features a series of subparallel faults which splay and recombine along strike (Fig. 6). The amount of vertical offset ranges up to 20 m. Cross faults with vertical displacement trend northwards, and are generally downthrown to the east.

Moderate changes in the strike direction of faults have resulted in the lenticular pattern of the structural zone.

The Athabasca Group sedimentary rocks in the hanging wall are stratigraphically equivalent to those in the footwall, and paleocurrent directions (which are oblique to the Key Lake structure) cross the fault zone without change. This suggests that, at the beginning of the Athabasca sedimentation, differences in topographic relief along the Key Lake structure were small (Ramaekers, 1985).

Sandstone south of the main structure is, in places, very friable, due to microbrecciation that caused fragmentation of

intergranular dravite rosettes and quartz overgrowths on detrital quartz grains (Fig. 7A)

Orebody

In detail, internal structures within the orebody are complex (De Carle, 1981). A face map from the 478 m bench in the Gaertner open pit (Fig. 8) shows a section across the ore zone, looking southwest. The unconformity is preserved in a four-metre-wide wedge between the uplifted northwestern block and the downthrown southeastern block. Southeasterly dipping ore veins are truncated along steep northwesterly dipping shears which, in turn, are crosscut by a clay seam. The latter appears to be terminated by another northwesterly dipping shear. The crosscutting relationships on this mining face indicate that the fractures hosting the ore veins are the oldest structures. Preliminary age dates of 1250 Ma for uraninite from sandstone-hosted veins seem to confirm this (A. Hohndorf, personal communication, 1986).

WALLROCK ALTERATION

Basement

Paleoweathering — remnant pre-Helikian weathering phenomena are present in a discontinuous hematitic zone in pale green biotite gneisses of the footwall and in the hanging wall, about five metres below the unconformity and within five metres of the orebody. This zone corresponds to the red-green zone defined by Macdonald (1980), and contains kaolinite, illite and chlorite.

Diagenetic alteration — the regionally developed bleaching and kaolinitization of the uppermost hematitic basement is ascribed to reducing diagenetic processes in the Athabasca Group. It is preserved only at distances of more than 10 to 15 m from visible mineralization. The underlying green zone, which in part may also result from diagenetic processes, is well preserved almost everywhere. Close to visible mineralization (less than about ten metres), the bleached portion of the alteration profile is overprinted by later hydrothermal alteration, mostly chloritization.

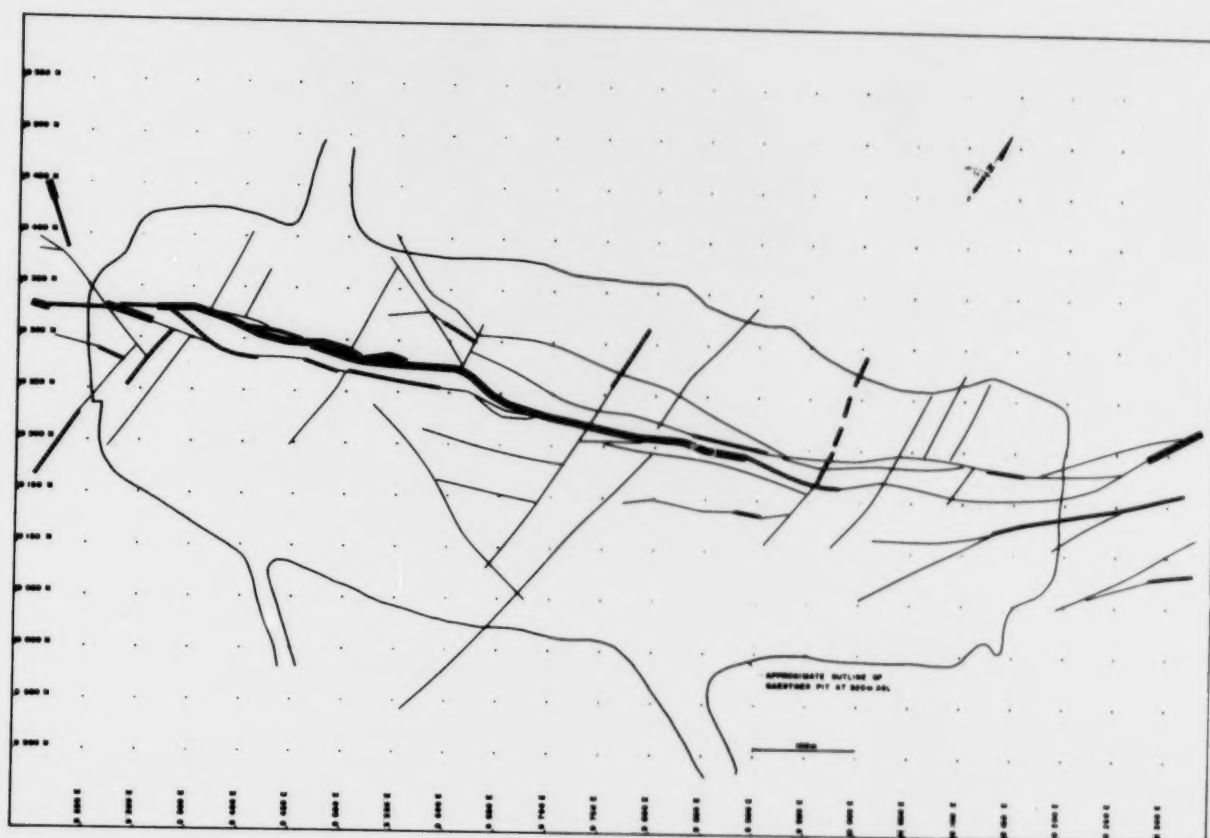


Figure 6. Vertical displacement at the unconformity: structural interpretation of the elevation of the Apebian — Helikian unconformity suggests that anastomosing faults with varying vertical displacement are present. Three different thickness of lines indicate throws of less than 5 m (thinnest lines), 5 to 10 m (medium thickness), and greater than 10 m (thickest lines).

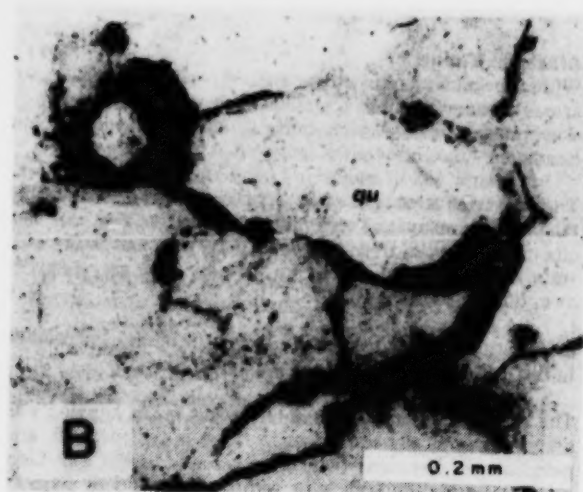
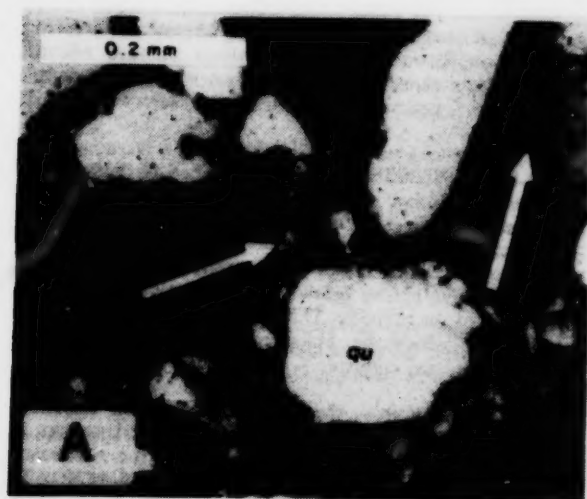


Figure 7. A) Friability of the Athabasca Group rocks is caused by microbrecciation: quartz overgrowth has been sheared off detrital quartz grains (qu) and most of the interstitial dravite spherulites are broken (arrows). *Crossed nicols.*

B) Pyrite (black) fills fractures between quartz grains (qu) and causes a black appearance of the sandstone at the periphery of the uranium orebody. *Parallel nicols.*

Hydrothermal alteration — strong pervasive chloritization of the gneiss immediately below the unconformity overprints the diagenetic bleaching in the area underlying and flanking the mineralization. It causes a green to dark green colouration of the gneiss. Fracture-controlled illitization and kaolinization as well as quartz-, dravite- and carbonate-veining are found peripheral to the strongly chloritized zone.

Athabasca Group

Within the limits of the Gaertner pit, the alteration of Athabasca Group sediments outside the mineralized zone consists of a series of processes which are partially listed below in their approximate paragenetic sequence:

- 1) illite overprint on a kaolinitic-illitic matrix. This phenomenon has also been identified above the Deilmann orebody and other unconformity-related deposits in the Athabasca Basin (Hoeve, 1982; Hoeve and Quirt, 1984; Hoeve et al, 1981; Sopuck, 1981). It may be associated with the initial mineralization phase.

Subsequent alteration events in proximity of the orebody and within mineralized portions of the Athabasca Group feature the redistribution of ore elements (U, Ni, As, Pb, etc.) and mobilization of Si, Fe, K, B and Mg from both ore and host rock:

- 2) quartz corrosion by kaolinite and chlorite, and replacement of illite by kaolinite and chlorite in combination with removal of interstitial purple hematite; this is an event observed also in unmineralized structures,
- 3) euhedral quartz overgrowth on dissolution fractures,
- 4) dravitzation of the kaolinite matrix and quartz overgrowth,
- 5) micro-brecciation.
- 6) pyritization on joints, pervasive pyritization,
- 7) impregnation of the matrix by carbonates,
- 8) corrosion of quartz and dravite by carbonates,
- 9) introduction of orange hematite and Fe-hydroxides, and
- 10) illite overprint on the kaolinite matrix.

These alteration processes postdate an ubiquitous early quartz overgrowth which replaced the detrital matrix.

With decreasing distance to the orebody, the following zonation has been observed (see Table 1):

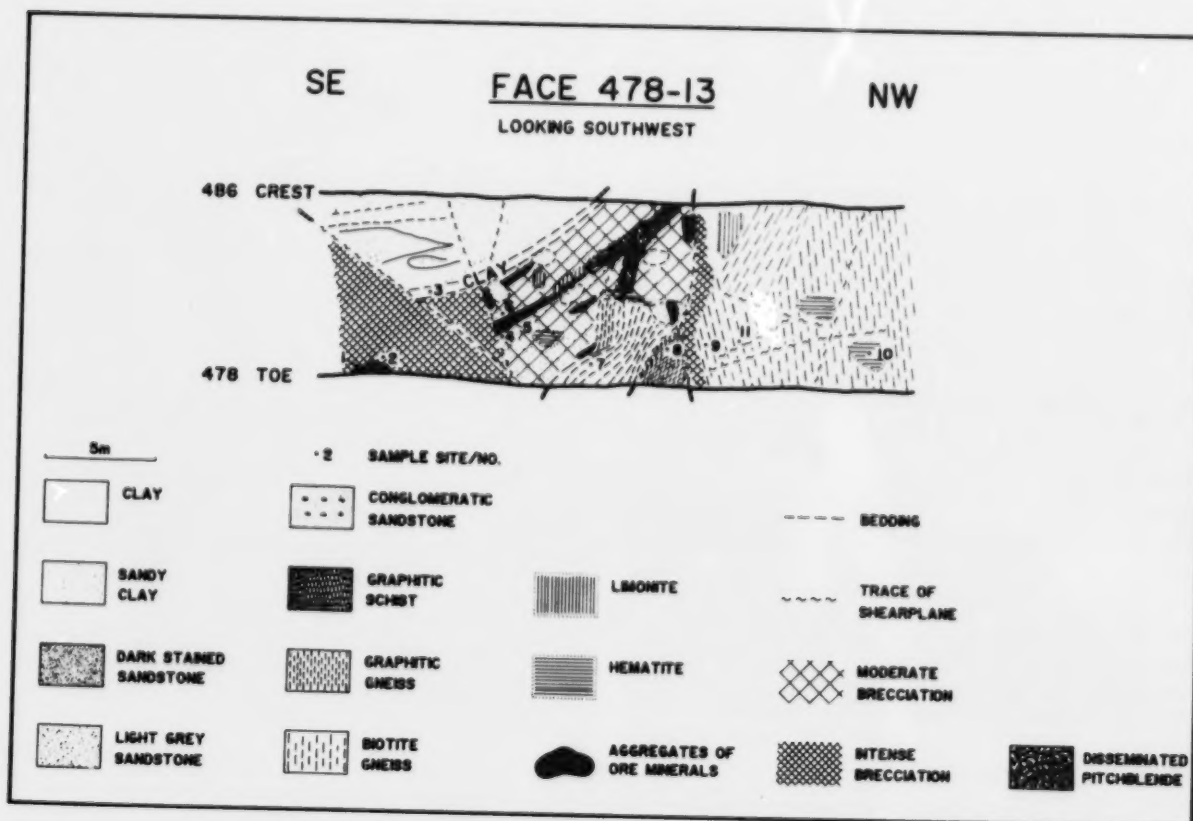


Figure 8. Mining face across the ore zone. Preserved U-Ni ore veins are dipping southeast. They are truncated by steeply north-dipping shears which, in turn, are severed by a shallowly southeast-dipping clay band. Disseminated pitchblende is present in the extension of crystalline ore veins and along some shears. The youngest tectonic event is represented by shallowly north-dipping shears which postdate the clay seam, and by the vertical fault which places the basement rocks (sample sites 7 to 10) against sandstone (sample sites 1 to 6). The Aphebian — Helikian unconformity is preserved above the basement rocks represented by rocks at sites 7 and 8.

- 1) An outermost zone in which specular hematite relicts indicate incomplete removal of hematite (at a distance generally exceeding 80 m from the centreline of the orebody, but closer in weakly tectonized rocks). Relict purple hematite is present in layers following the bedding and as Liesegang rings crosscutting sedimentary features. Hematite forms well crystallized platelets postdating dravite spherules in a clay-mineral matrix. Dravite also occurs as an overgrowth on detrital tourmaline. Detrital biotite is bleached and converted into sericite and, locally, into kaolinite. Later limonitization overprints the clay matrix in places.

The illite: chlorite: kaolinite ratios range up to 92:0:8 (illite + chlorite + kaolinite = 100).

The Kuebler index of illites ranges from 4.7 to 5.3 indicating a high crystallinity and formation under deep burial conditions (Hoeve et al, 1981). The illite peak intensity ratios are greater than 0.49. This suggests that the illites tend toward an aluminous composition which is characteristic for alteration haloes (Hoeve, 1982).

Uranium concentrations are about one ppm in hematitic portions, increasing to several tens of ppm in limonitic areas.

- 2) A discontinuous friable zone (within approximately 40 m of the centreline of the orebody) is characterized by microbrecciation. Quartz overgrowth is often broken off and separated from the detrital quartz grains. Dravite spherulites are fractured (Fig. 7A). Kaolinite generally predominates over illite. Chlorite is absent. Uranium contents within this zone vary from 3 to 15 ppm.
- 3) A pyritic zone with a carbonate overprint of varying intensity is located at the periphery of the high-grade

orebody. The rocks in this zone have a black colour due to the presence of pyrite. In general, the pyrite zone is oriented parallel to the Key Lake structure but extends along cross faults up to a distance of 100 m. Quartz overgrowths and the kaolinite matrix are corroded and partially replaced by dravite which, in turn, is locally corroded and substituted by siderite. Pyrite is present as cubic crystals, as disseminations in the matrix and as stringers (Fig. 7B). Kaolinite is the main clay mineral in this zone and, in most samples, chlorite is also present while illite is virtually absent. Uranium values range from 5 to 5000 ppm. Uranium mineralization is preferentially associated with structures parallel to the Key Lake Fault.

Mineralized Zone

The sandstone in the centre of the Key Lake structure shows kaolinitization and chloritization of the matrix with concomitant corrosion of detrital quartz grains, followed by dravitization and pyritization of the kaolinite matrix and, finally, by the formation of carbonates. Hematite locally overprints siderite. Secondary pores are commonly filled with siderite or iron hydroxides. Illite of low crystallinity is present in a few localities.

As a result of intensive kaolinitization, round sandstone relicts formed in discontinuous zones parallel to the main Key Lake structure. These were shown as a breccia zone on early cross-sections (Dahlkamp, 1978). They resemble the "zone a boules" which has been observed at Cluff Lake (Ey et al, 1985). This type of alteration is also present in a structure parallel to the Key Lake zone as well as in cross faults.

In detail, clay replacement of quartz appears to have started from bedding planes and fractures, and to have progressed towards unfractured centres. A continuous transition zone between clay and sandstone is locally preserved (Fig. 9A). Despite the conversion of quartz clasts and matrix to kaolinite, original textures were, in many places, preserved, such that

Table 1. Zonation of alteration in the Athabasca Group at a level of approximately ten metres above the unconformity.

Alteration feature	Zone with hematite relicts (more than 80 m from ore)	Friable zone (ca. 40 m from ore)	Pyrite-carbonate zone (less than 40 m from ore)	Sandstone relicts in mineralized zone
Quartz overgrowth	•	•	•	•
Hematite relicts	•			
Illite > (kaolinite and chlorite)	•			
Illite < (kaolinite and chlorite)		•	•	•
Kaolinite corroding quartz			•	•
Strong chloritization			•	•
Dravite corrodes quartz and impregnates kaolinite matrix	Rare		•	•
Microbrecciation	Rare	•		
Pyrite			•	•
Carbonates replace kaolinite, quartz and dravite		Rare	•	•
Hematite on siderite and Fe-hydroxides in pores		Rare	•	•
Illite replaces kaolinite and dravite				•
Uranium (ppm)	1 ppm (>10 rare)	3-15 ppm	5-5000 ppm	86-3000 ppm

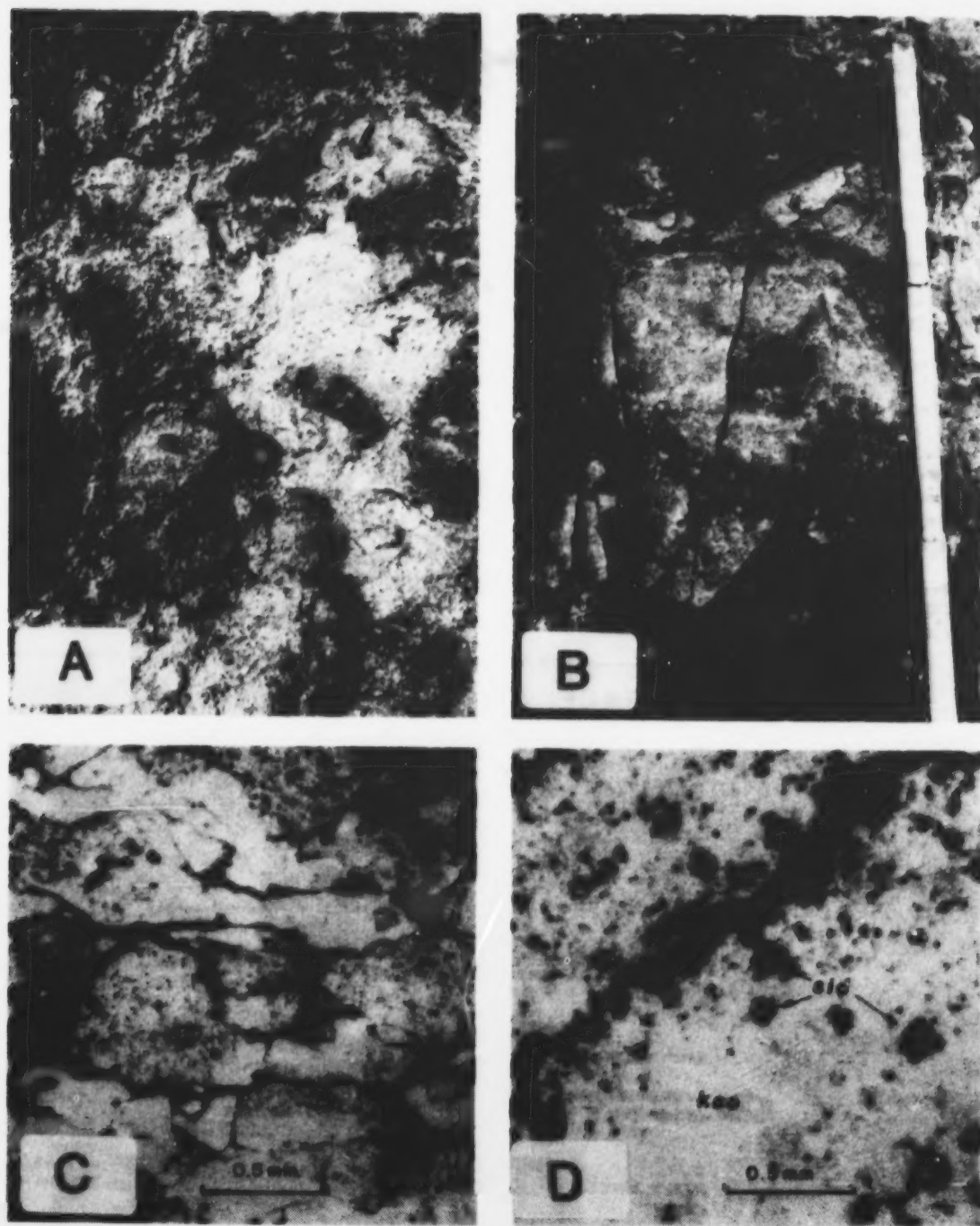


Figure 9. A) Dark grey sandstone relicts are embedded in light grey to white kaolinite. The sandstone-clay boundary is transitional (lens cap for scale).

B) Sandstone relict embedded in clay; the sharp boundary between sandstone and clay indicates shearing at the interface (scale in centimetres).

C) Kaolinitized quartz grains were elongated and flattened by shearing, causing a pseudo-gneissic texture. *Parallel nicols*.

D) Heavy mineral layer consisting of magnetite, zircon and tourmaline in completely kaolinitized sandstone; euhedral siderite crystals (sid) in kaolinite (kao) matrix. *Parallel nicols*.

quartz pebbles remain recognizable by slight colour differences.

Kaolinitized grains and pebbles are apparently greater in size than their original siliceous counterparts. This suggests that a volume increase has taken place as a result of the clay alteration. The increase in grain size may also be partially due to coalescing recrystallization.

A sharp boundary between round sandstone relicts and the clay envelope along with slickensides in the clay suggest syn- or post-alteration tectonic activity (Fig. 9B). Possibly due to volume increase, clay-altered material was mobilized into fractures. The kaolinitized clasts thereby became flattened and elongated parallel to the fracture walls, resulting in a pseudo-gneissic texture (Fig. 9C).

Heavy-mineral layers consisting of zircon, tourmaline and magnetite are locally preserved (Fig. 9D) and are traceable around sandstone relicts (Fig. 10). The distortion of the layers confirms on a larger scale (than boundary relationships and slickensiding described above) post-alteration tectonic activity.

In sandstone relicts, the uranium contents range from 86 ppm to about 3000 ppm. Kaolinite/chlorite mixtures that envelope sandstone relicts assay from 390 ppm to almost 4 per cent U.

Other clays, which surround ore aggregates in the ore zone, have been identified as mixed-layer clays and septechnorites. They assay up to 7 per cent U and 16 per cent Ni.

The clay alteration and uranium values within, and in close proximity to, the mineralized zone are illustrated on a face map from the 470 m bench in the Gaertner pit (Fig. 11).

The northeasternmost rock unit consists of cordierite-biotite gneisses with irregular hematite patches, interpreted as being due to paleoweathering. They are underlain by graphitic gneisses ("Main Graphite") which are folded about a horizontal axis trending parallel to the regional foliation. The uranium values in this unit range from 1 to 26 ppm with high Ni/U ratios. The clay mineralogy is dominated by illite and chlorite. Kaolinite is present in only one sample.

The basement rocks are separated from the high-grade ore zone by a steeply dipping fault which truncates the folded graphitic gneiss.

The sandstone southeast of the fault is heavily sheared and clay-altered. The clay mineralogy is dominated by kaolinite and chlorite. Illite is absent.

Massive ore aggregates consist of slabs which are mixed with sandstone relicts. At the contact with the graphitic gneiss, the slabs are oriented parallel to the fault plane.

Another zone of uranium mineralization is present in a kaolinitized/chloritized structure with round sandstone relicts at the southeast end of the mining face.

A synopsis of the alteration is given in Fig. 12.

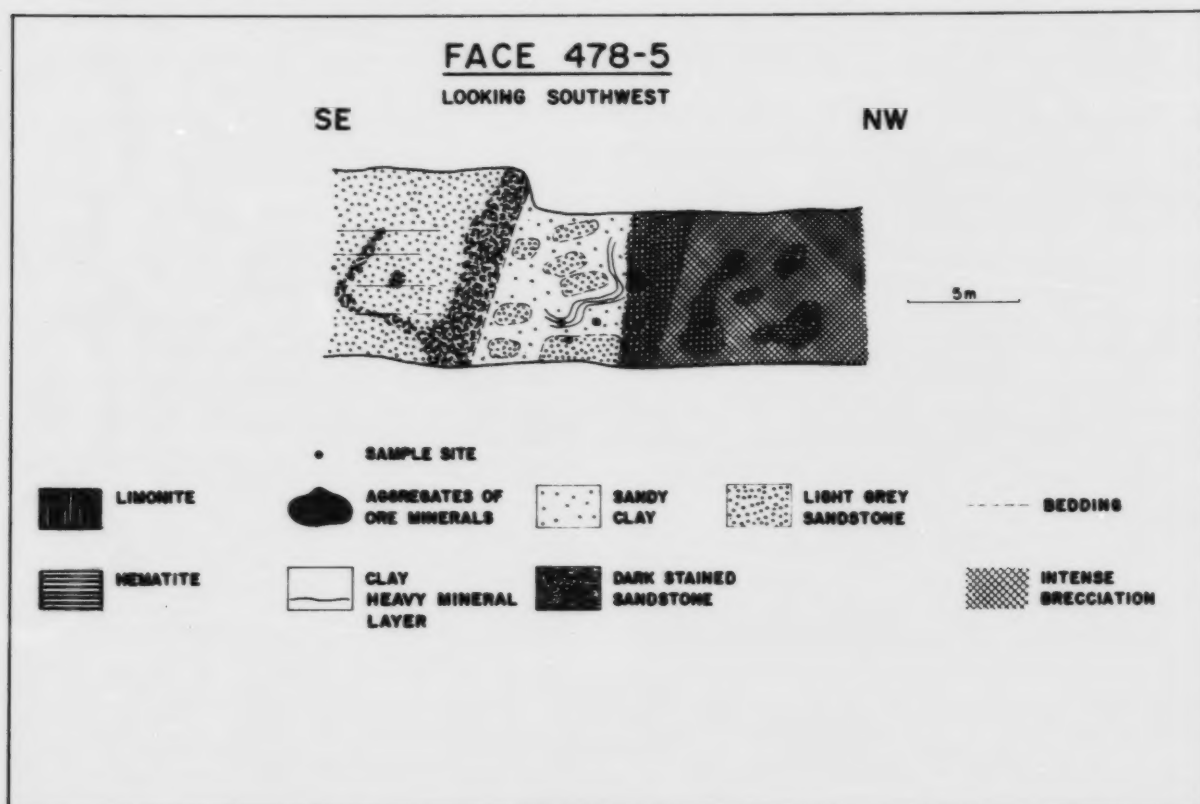


Figure 10. Clay alteration of sandstone southeast of the ore zone has resulted in the development of round sandstone relicts. The clay material between the sandstone relicts contains deformed heavy-mineral layers. The deformation took place after the clay alteration.

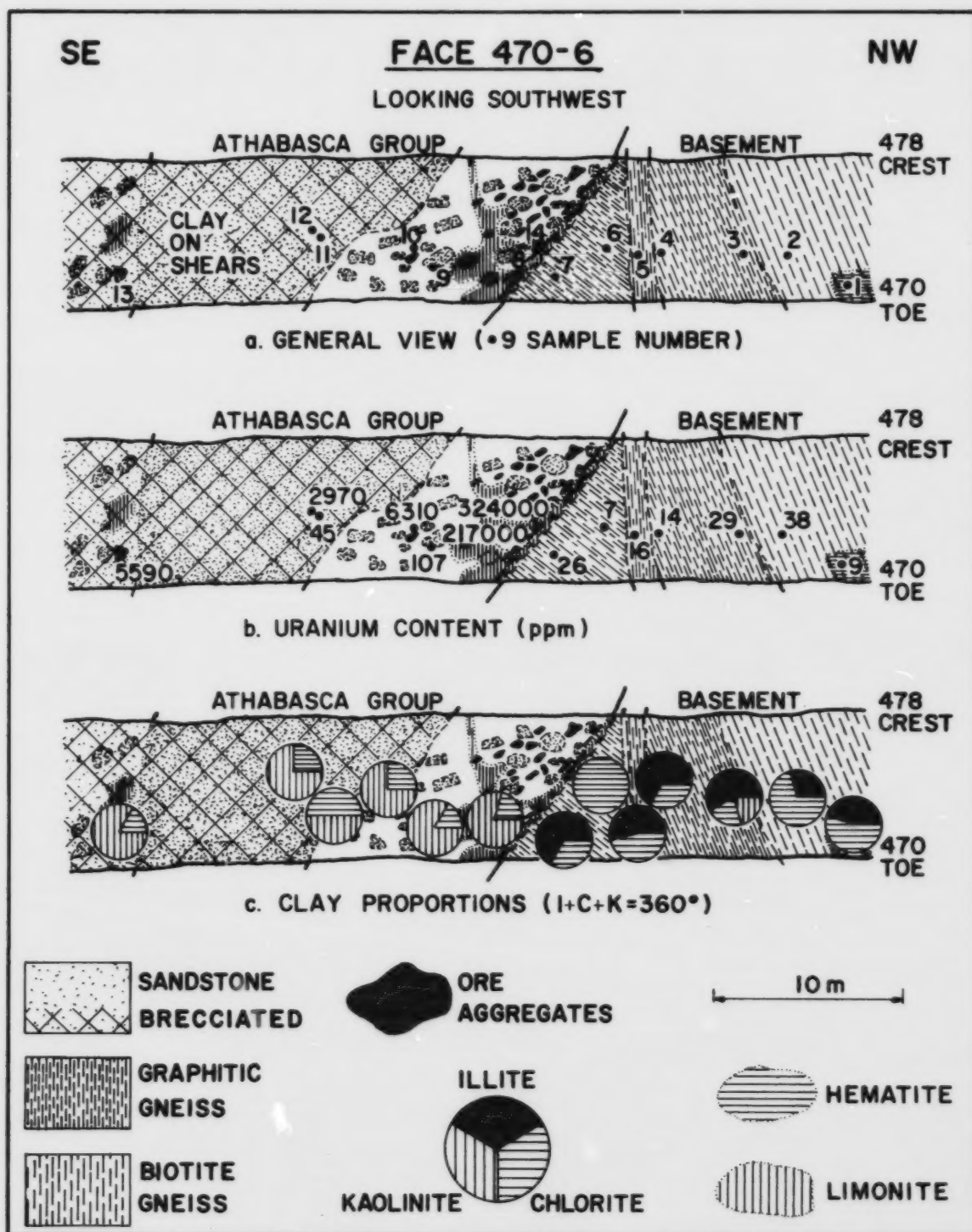


Figure 11. Post-ore and post-alteration faulting: the downthrown southeastern sandstone block is dominated by a kaolinite-chlorite clay mineralogy while the uplifted northwestern basement block is mostly illitic-chloritic. The high-grade mineralization is concentrated in a narrow zone within the downthrown block and consists of U-Ni ore aggregates mixed with low-grade sandstone relicts. Note that the orientation of the mining face is not perpendicular to the trend of the fault which separates the uplifted basement block from the downthrown sandstone block. The fault therefore appears to dip to the southeast although it is, in fact, subvertical.

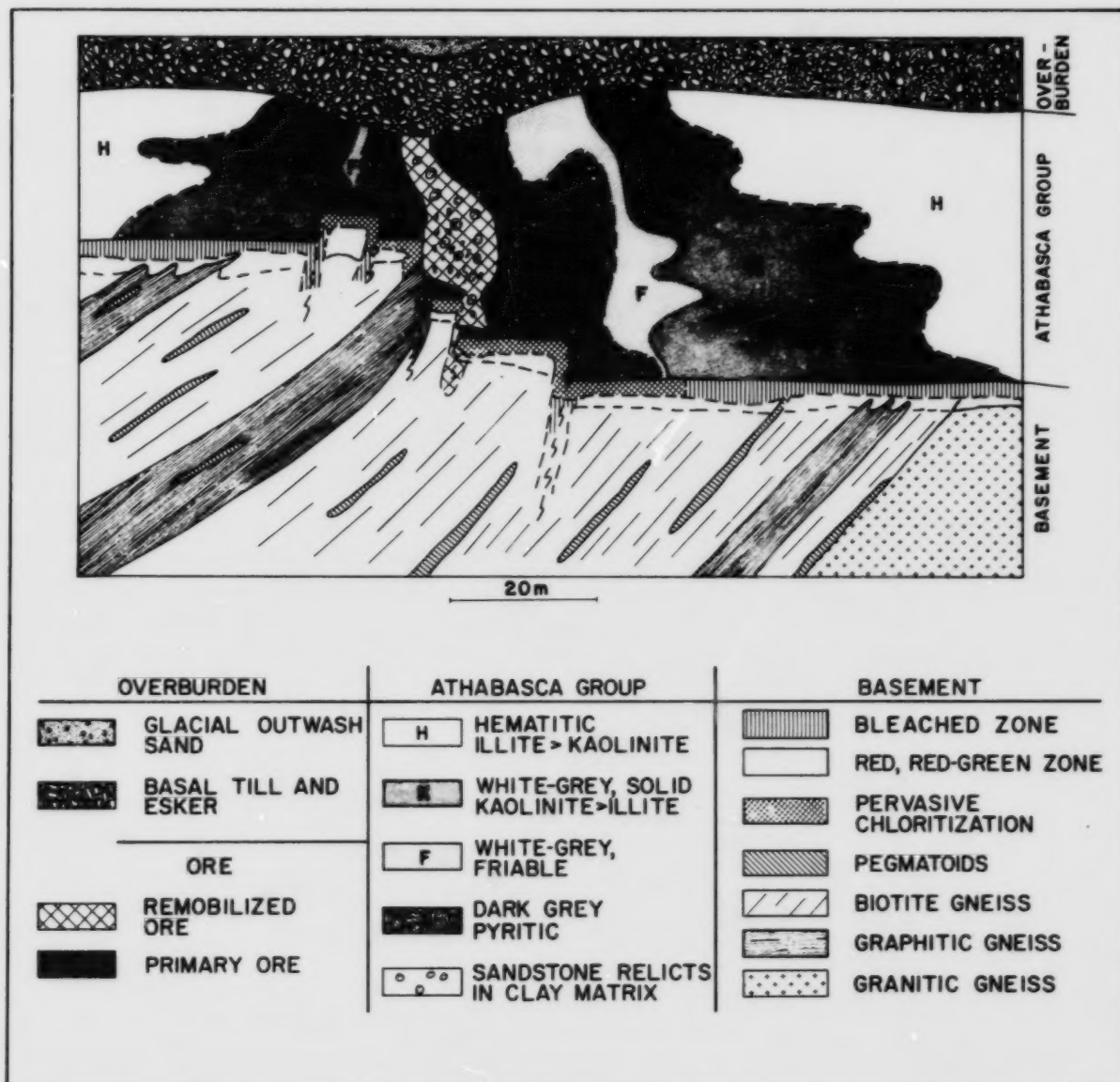


Figure 12. Schematic zonation of the alteration surrounding the Gaertner orebody.

ORE

MINERALOGY

Uranium ore minerals are uraninite (anisotropic), pitchblende (isotropic), sooty pitchblende and coffinite. The latter two minerals are present mainly in rocks of the Athabasca Group. Secondary uranium (U^{++}) and nickel minerals are virtually absent in freshly mined ore.

Nickel arsenides, sulpharsenides and sulphides show progressive replacement relationships such that arsenic contents decrease in favour of sulphur. These relationships have been described in more detail by Von Pechmann (1985) who has also comprehensively listed uranium and nickel minerals so far identified at Key Lake.

Several pulses of uranium mineralization, separated from one-another by phases of brecciation and remobilization, have been recognized (Dahlkamp and Tan, 1976). The oldest uranium ore consists of crystalline anisotropic uraninite dated at 1250 ± 34 Ma (Gaertner orebody; Hohndorf et al, 1985) and 1350 ± 4 Ma (Deilmann orebody; Trocki et al, 1984), followed by mineralization episodes at about 903 ± 40 Ma (mostly coffinite) and 286 ± 12 Ma (Hohndorf et al, 1985).

ORE DISTRIBUTION

The uranium-nickel content of the sandstone and the basement wallrock increases rapidly toward the high-grade mineralization, and concentrations of about 10 ppm of uranium are found less than 30 m from the orebody.

On the basis of shape of ore aggregates, mineralogy, and host rock, five ore types are distinguishable:

- 1) sandstone-hosted ore veins with well defined walls are locally preserved over a length of several metres, but generally only fragments are found; this ore type occurs at the periphery and in less clay-altered portions of the high-grade core of the orebody; the ore consists of repeatedly fractured uraninite, pitchblende, coffinite, carbonates, and Ni minerals;
- 2) large, nodular U-Ni masses up to two m thick and five m wide; this type preferentially occurs immediately above the unconformity and in the core of the high-grade zone;
- 3) clay-hosted lustrous or dull pitchblende; the colour of the clay is generally red as a result of hematite and limonite impregnation, but black, white and green types are present in irregular zones; this ore variety represents the remaining mineralization after corrosive clay alteration (Figs. 13 B and 13 C); the clay minerals are kaolinite, chlorite, montmorillonite, mixed-layer clays or septechlorite, or combinations thereof; where the ore is hosted in hematitic clay, a reduction halo of white sheet silicates surrounds the relicts of the ore minerals;
- 4) disseminated sooty pitchblende in dark grey sandstone which may have been mobilized as a result of the corrosive clay alteration; and

- 5) basement-hosted mineralization present in shears which extend downward to a depth of approximately 30 m below the unconformity.

Both veins (1) and nodular aggregates (2) have been fragmented and dislocated (Fig. 13A).

GLACIAL EROSION

Glacial overburden is present with a thickness ranging up to several decametres. Fracture zones in the bedrock as well as strongly clay-altered material have been preferentially eroded and filled (Fig. 14).

Basal till as well as esker material are in contact with the mineralized zone (Fig. 15). Basal till contains U-Ni mineralized boulders in the down-ice direction (approximately 145°). Ore-bearing esker strands were diverted along north-south trending cross structures.

Glacial outwash sand covers both basal till and esker ridges in the pit area. It locally contains ore grains (Fig. 15) and cobbles. The presently observed irregular distribution of pitchblende grains indicates that they have been dissolved by groundwater, implying that uranium redistribution is an ongoing process.

CONCLUSION

The oldest uranium mineralization in the Gaertner orebody fills fractures in the Athabasca Group rocks above and

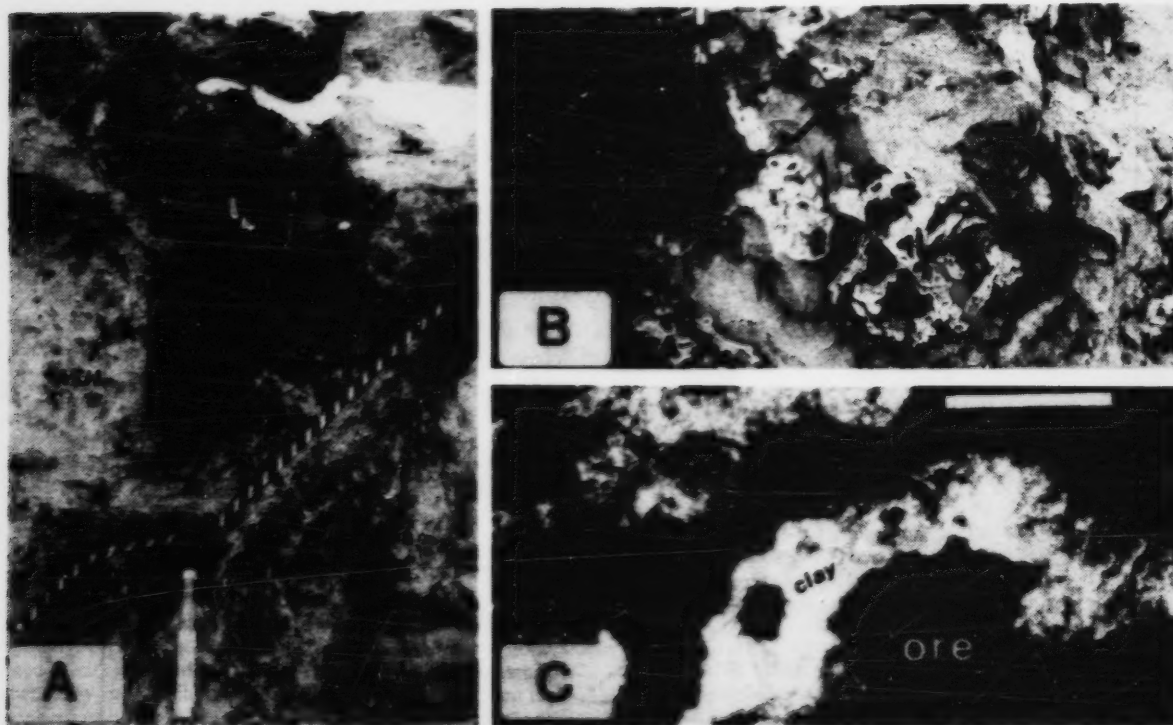


Figure 13. Post-ore events. A) Fragments of high-grade ore veins are wedged between weakly altered Athabasca quartz-pebble conglomerate (left, and right-top) and graphitic gneiss (right-bottom); ATH = Athabasca Group conglomerate. Felt pen for scale.

B) Corroded ore relicts are surrounded by reduction rims in hematitic clay. Pencil for scale.

C) On a microscopic scale, the corrosion becomes evident by embayments of the opaque ore; hem = hematite. Scale = 0.75 mm.

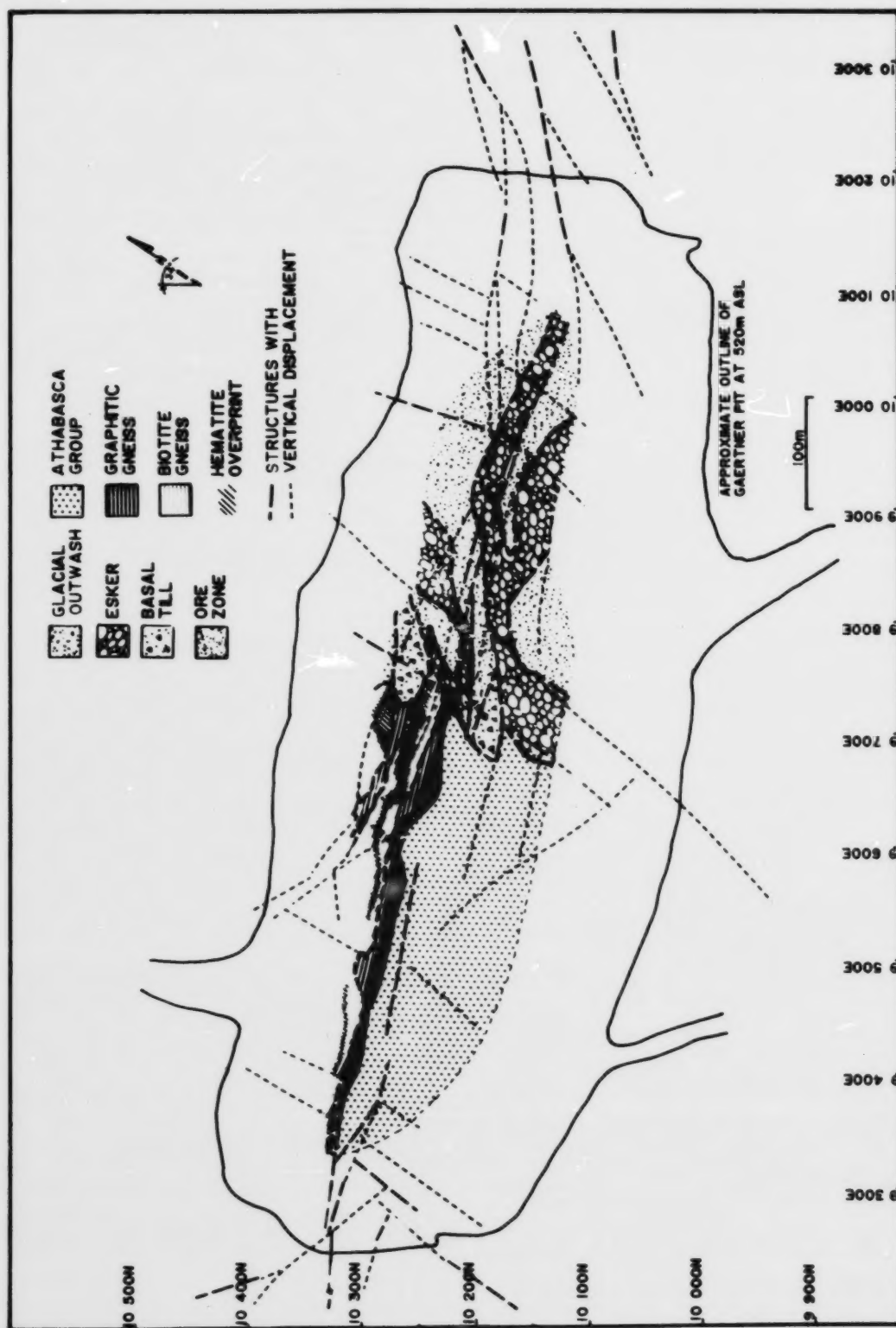


Figure 14. Geological plan, bench 478 m. The northeastern portion of the open pit is mostly occupied by glacial overburden. The southwestern limit (of basal till, esker material and outwash sand) is controlled in part by a set of northerly trending cross faults in the subcrop.

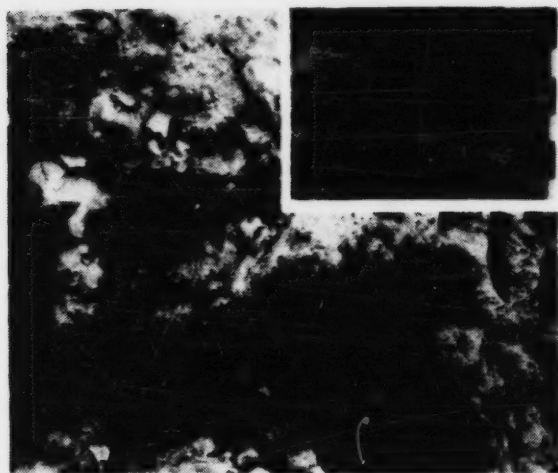


Figure 15. Overburden, showing the contact between esker material (top) and ore (bottom). Hammer as scale. The insert (top-right) shows layered glacial outwash sand which contains pitchblende grains; the pitchblende grains were partially dissolved along bedding planes. Scale in centimetres.

flanking plastically deformed graphitic gneisses. Diapiric movement within the graphitic gneisses (Strnad, 1981), suggested by disharmonic folding and shearing along graphite-lined slide-planes, may have caused "buckling" of the basement and, consequently, fracturing of overlying sandstone of the Manitou Falls Formation. These fractures extended into basement rocks. They provided channelways for potassium-bearing fluids that caused the illite halo in overlying rocks of the Athabasca Group.

The basement probably attained its highest level in the hanging wall above the graphitic gneisses (see Fig. 4 and illustrations in Dahlkamp and Tan, 1976; Dahlkamp, 1978; Gatzweiler et al, 1979; Kirchner et al, 1980). This indicates that a post-Athabasca horst (Strnad, 1981), similar to those at McClean Lake (Wallis et al 1983), Zone 11A at Dawn Lake (Clarke and Fogwill, 1985), and Cigar Lake (Fouques et al, 1986), was present which, in the case of the Gaertner deposit, was subsequently faulted along a steeply dipping structure.

Repeated fracturing of ore veins provided space for the precipitation of polymetallic mineralization until 900 Ma. The basin-wide kaolinitization event around 300 Ma resulted in corrosion and redistribution of the ore metals. This accords with the findings of Trocki et al (1984) who dated the lead fractionation at 300 Ma.

The kaolinitization overprinted the earlier illite halo. Where the kaolinitizing solutions came under the influence of high Mg and Fe chemical activity, particularly in the ore zone, mixed-layer clays and chlorites were precipitated. Potassium expelled by the kaolinitization may have been driven into the periphery resulting in the enhancement of the illite halo there.

Later tectonic activity (possibly at about 100 Ma) affected the argillitized deposit; part of the orebody was downfaulted as the result of tectonic adjustment. No hydrothermal activity was associated with this event.

REFERENCES

- Agnerian, H., and K.P.L. Kwan, 1983, Lithological compilation of the Key Lake area: Interim report for the Saskatchewan Uranium Joint Venture.
- Armstrong, R.L., and P. Ramaekers, 1985, Sr isotopic study of Helikian sediments and diabase dikes in the Athabasca Basin, northern Saskatchewan: *Canadian Journal of Earth Sciences*, v. 22, p. 399-407.
- Bell, K., 1981, A review of the geochronology of the Precambrian of Saskatchewan — some clues to uranium mineralization: *Mineralogical Magazine*, v. 44, p. 371-378.
- Clarke, P.J., and W.D. Fogwill, 1985, Geology of the Dawn Lake uranium deposits, northern Saskatchewan, in T.I.I. Sibbald and W. Petruk, eds., *Geology of uranium deposits: Canadian Institute of Mining and Metallurgy Special Volume 32*, p. 132-139.
- Dahlkamp, F.J., 1978, Geologic appraisal of the Key Lake U-Ni deposits, northern Saskatchewan: *Economic Geology*, v. 73, p. 1430-1449.
- Dahlkamp, F.J., and H.B. Tan, 1976, Geology and mineralogy of the Key Lake U-Ni deposits, northern Saskatchewan, Canada, in M.J. Jones, ed., *Geology, mining and extractive processing of uranium: Institute of Mining and Metallurgy, London*, p. 145-157.
- De Carle, A., 1981, Geology of the Key Lake deposits — an overview: Canadian Institute of Mining and Metallurgy, Geology Division, Uranium Field Excursion, 1981, p. 110-130.
- Ey, F., F. Gauthier-Lafaye, F. Lillie, and F. Weber, 1985, A uranium unconformity deposit: the geological setting of the D orebody (Saskatchewan, Canada), in R. Laine, D. Alonso, and M. Svab, eds., *The Carswell Structure uranium deposits, Saskatchewan: Geological Association of Canada Special Paper 29*, p. 121-138.
- Fortuna, P., 1983, Key Lake Project — Quarternary Investigation: unpublished consultant's report for Key Lake Mining Corporation by Eldor Resources Limited.
- Fouques, J.P., M. Fowler, H.D. Knipping, and K. Schimann, 1986, Le gisement d'uranium de Cigar Lake: decouverte et caracteristiques generales: *Canadian Institute of Mining and Metallurgy Bulletin*, v. 79, no. 886, p. 70-82.
- Gatzweiler, R., K. Lehnert-Thiel, D. Clasen, B.H. Tan, V. Voultsidis, J.G. Strnad, and J. Rich, 1979, The Key Lake uranium-nickel deposits; *Canadian Institute of Mining and Metallurgy Bulletin*, July 1979, p. 1-7.
- Gatzweiler, R., B.D. Schmeling, and E.H. Tan, 1980, History of exploration of the Key Lake uranium deposits: Advisory Group Meeting on Case History of Uranium Exploration, International Atomic Energy Agency, Vienna, November 1979.
- Hoeve, J., 1982, Clay mineral host rock alteration at the Key Lake uranium deposit, northern Saskatchewan:

- Saskatchewan Research Council Publication G-745-7-C-82, 26 p.
- Hoeve, J., and T.I.I. Sibbald, 1978, On the genesis of Rabbit Lake and other unconformity-type uranium deposits in northern Saskatchewan, Canada: *Economic Geology*, v. 73, p. 1450-1473.
- Hoeve, J., K. Rawsthorn, and D. Quirt, 1981, Uranium metallogenic studies: clay mineral stratigraphy and diagenesis in the Athabasca Group, in J.E. Christopher and R. Macdonald, eds., *Summary of Investigations 1981*, Saskatchewan Geological Survey: Saskatchewan Mineral Resources Miscellaneous Report 81-4, p. 76-89.
- Hoeve, J., and D. Quirt, 1984, Uranium mineralization and host rock alteration in relation to clay mineral diagenesis and evolution of the Middle-Proterozoic Athabasca Basin, northern Saskatchewan, Canada: Saskatchewan Research Council Publication R855-2-A-84.
- Hohndorf, A., H. Lenz, E. von Pechmann, V. Voultsidis, and I. Wendt, 1985, Radiometric age determinations on samples of Key Lake uranium deposits, in T.I.I. Sibbald and W. Petruk, eds., *Geology of uranium deposits: Canadian Institute of Mining and Metallurgy Special Volume 32*, p. 48-53.
- Kirchner, G., and H.B. Tan, 1977, *Prospektion, Exploration und Entwicklung der Uranlagerstaette Key Lake*, Kanada: *Erzmetall*, v. 30, p. 583-589.
- Kirchner, G., K. Lehnert-Thiel, J. Rich, and J.G. Strnad, 1980, The Key Lake U-Ni deposits: a model for Lower Proterozoic Uranium Deposition: *Proceedings of the International Symposium on the Pine Creek Geosyncline*, p. 617-629.
- Lewry, J.F., T.I.I. Sibbald, and C.J. Rees, 1978, Metamorphic patterns and their relation to tectonism and plutonism in the Churchill Province of northern Saskatchewan, in *Metamorphism in the Canadian Shield: Geological Survey of Canada Paper 78-10*, p. 139-154.
- Macdonald, C.C., 1980, Mineralogy and geochemistry of a Precambrian regolith in the Athabasca Basin: unpublished MSc thesis, Department of Geological Sciences, University of Saskatchewan, Saskatoon, 151 p.
- Money, P.L., 1968, The Wollaston fold belt system, Saskatchewan-Manitoba: *Canadian Journal of Earth Sciences*, v. 5, p. 1489-1504.
- Money, P.L., A.J. Baer, B.P. Scott, and R.H. Wallis, 1970, The Wollaston Lake belt, Saskatchewan, Manitoba, Northwest Territories, in A.J. Baer, ed., *Symposium on basins and geosynclines of the Canadian Shield: Geological Survey of Canada Paper 70-40*, p. 170-197.
- Ramaekers, P., 1979, Stratigraphy of the Athabasca Basin, in J.E. Christopher and R. Macdonald, eds., *Summary of Investigations 1979*, Saskatchewan Geological Survey: Saskatchewan Mineral Resources Miscellaneous Report 79-10, p. 154-160.
- Ramaekers, P., 1980, Stratigraphy and tectonic history of the Athabasca Group (Helikian) of Northern Saskatchewan, in J.E. Christopher and R. Macdonald, eds., *Summary of Investigations 1980*, Saskatchewan Geological Survey: Saskatchewan Mineral Resources Miscellaneous Report 80-4, p. 99-106.
- Ramaekers, P., 1981, Hudsonian and Helikian basins of the Athabasca region, northern Saskatchewan, in F.H.A. Campbell, ed., *Proterozoic Basins of Canada: Geological Survey of Canada Paper 81-10*, p. 219-233.
- Ramaekers, P., 1985, Structural geology of the Gaertner pit, Key Lake Mine, Saskatchewan: Unpublished consultant's report for Key Lake Mining Corporation.
- Ramaekers, P., and C.E. Dunn, 1977, Geology and geochemistry of the eastern margin of the Athabasca Basin, in C.E. Dunn, ed., *Uranium in Saskatchewan*, Saskatchewan Geological Society Special Publication 3, p. 297-332.
- Sopuck, V.J., 1981, Lithogeochemical studies — Deilmann uranium deposit: Saskatchewan Research Council Publication G-740-11-C-81, 52 p.
- Stockwell, C.H., 1970, Introduction to geology of the Canadian Shield, in R.J.W. Douglas, ed., *Geology and Economic Minerals of Canada: Geological Survey of Canada Economic Geology Report 1*, 5th edition, p. 44-54.
- Strnad, J., 1981, The evolution of Lower Proterozoic epigenetic stratabound uranium deposits (a concept), in *Metallogenesis of Uranium: Proceedings of 26th International Geological Congress at Paris, France, 1980*, section 13, theme 2.2, Geoinstitut, Beograd, Yugoslavia, p. 99-162.
- Tan, H.B., 1977, Geochemical case history in the Key Lake area, in C.E. Dunn, ed., *Uranium in Saskatchewan: Saskatchewan Geological Society Special Publication 3*, p. 323-330.
- Trocki, L.K., D.B. Curtis, A.J. Gancarz, and J.C. Banar, 1984, Ages of uranium mineralization and lead loss in the Key Lake uranium deposit, northern Saskatchewan, Canada: *Economic Geology*, v. 79, p. 1378-1386.
- Von Pechmann, E., 1985, Mineralogy of the Key Lake U-Ni orebodies, Saskatchewan, Canada: evidence for their formation by hypogene hydrothermal processes, in T.I.I. Sibbald and W. Petruk, eds., *Geology of uranium deposits: Canadian Institute of Mining and Metallurgy Special Volume 32*, p. 27-37.
- Wallis, R.H., N. Saracoglu, J.J. Brummer, and J.P. Golightly, 1983, Geology of the McClean uranium deposits, in E.M. Cameron, ed., *Uranium Exploration in Athabasca Basin, Saskatchewan, Canada: Geological Survey of Canada Paper 82-11*, p. 71-110.
- Winkler, H.G.F., 1967, *Die Genese der metamorphen Gesteine*, (2nd edition): Springer, Berlin, Heidelberg, New York, 237 p.
- Young, P., R. Gatzweiler, and W. Floter, 1982, Die Entwicklung der Uranerzlagerstaette von Key Lake/Saskatchewan, Kanada: *Erzmetall*, v. 35, no. 10, p. 489-510.

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THE ECONOMIC POTENTIAL OF THE WESTERN END OF THE ATHABASCA BASIN

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ABSTRACT

The western end of the Athabasca Basin in Alberta and Saskatchewan has considerable economic potential. The uranium deposits with strong surface expressions have been found (Cluff Lake, Maurice Bay, Fond du Lac, Stewart Island), so future exploration must concentrate on buried deposits. In general, these western deposits are not spatially associated with the strong graphitic conductors found with the eastern Athabasca Basin uranium deposits. Therefore, new exploration techniques may be required to locate hidden "western type" deposits.

In Alberta, the unconformity beneath the Athabasca Group is less than 600 m deep beneath a total area of more than 6,000 km² and more than 600 m deep beneath some 2,000 km² of ground. The sub-Athabasca basement consists predominantly of granitoid rocks, with local developments of granite gneiss, metasediments and mylonites. These rocks are equivalent, in part, to those cropping out in the mapped basement north of Lake Athabasca and at Cluff Lake. In addition to diagenetic events recognizable within the Athabasca Group, four alteration events have been identified within the basement. Three of these events (saprolite formation, hydrothermal alteration and bleaching) were leaching processes which produced a rock depleted in most economic minerals. The fourth type of alteration was recognized only locally and has resulted in anomalous enrichment of certain elements (Si, K, Ca, Na, Pb, Ni, Ba, Co, Sr, Zn and U), similar to the enrichment found around some deposits in the eastern part of the Basin and thus possibly related to ore genesis. This enrichment (assay values are as high as 292 ppm uranium, 2700 ppm lead, 2320 ppm zinc and 0.08 oz. gold per ton), temperature anomalies and high gamma counts together indicate that the area has considerable economic potential.

Exploration in the western end of the Athabasca Basin has so far been limited to uranium, and has concentrated on deposits with a surface expression. Only recently have new techniques, developed in the search for eastern Athabasca Basin uranium deposits, been applied. However, the known western deposits appear to differ geologically in several respects from their counterparts in the Wollaston Domain. Most significantly, they seem not to be associated with well developed graphitic conductors. Instead, they are more strongly associated with other rock types, stratigraphic contacts, regional structures, and mylonites. Discovery of hidden uranium deposits in the west may entail detailed geological and structural mapping through geophysics and stratigraphic drilling, followed by target drilling of promising areas and geochemical studies to define alteration haloes.

In addition to uranium, gold, lead-zinc and phosphate mineralization should be looked for during exploration.

INTRODUCTION

The discovery of many large unconformity-type uranium deposits beneath the eastern end of the Athabasca Basin has overshadowed the economic potential of the Basin farther west. The purpose of this paper is to outline the economic potential of the western end of the Basin with respect to uranium, lead-zinc, gold and phosphate.

Exploration for uranium in the western end of the Athabasca Basin has been dramatically successful in places (Cluff Lake) or has led to the discovery of subeconomic deposits (Maurice Bay, Fond du Lac, Stewart Island) (Fig. 1). However, the standard of exploration has varied greatly, and large areas

have been examined in only a cursory manner. Also, recent geophysical advances have increased the thickness (of sandstone and glacial overburden) through which areas of interest at the sub-Athabasca unconformity are detectable. In Alberta alone, the sub-Athabasca unconformity is within 600 m of the surface in areas which together cover more than 6000 km² and which are only recently being explored using expertise gained at the large uranium deposits to the east.

Anomalously high concentrations of lead, zinc, gold and phosphate within and beneath the Athabasca Group have been found. However, exploration specifically for these has not been undertaken, so occurrences may have been missed.

This article focuses on the western end of the Athabasca Basin in Alberta. It outlines the geology of the basement and cover in

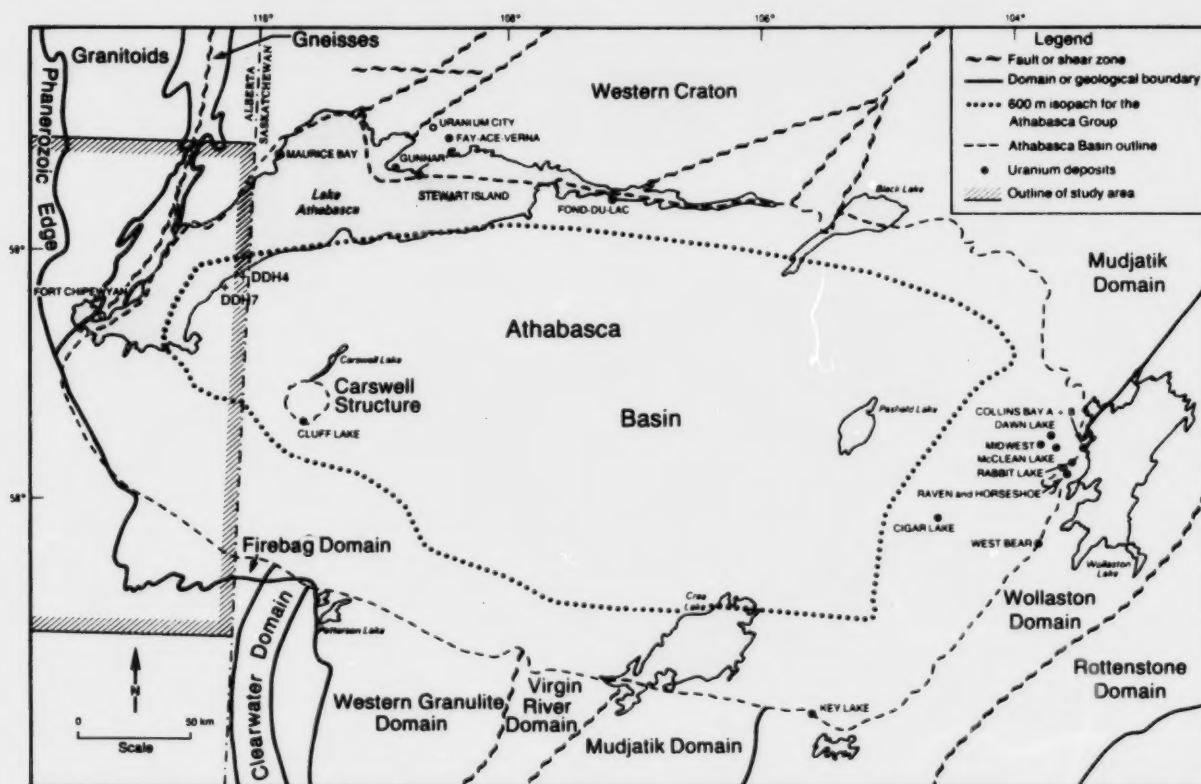


Figure 1. Geological sketch map of the Athabasca Basin showing the location of major uranium deposits and outlining the study area.

the study area, discusses the chemical alteration which has occurred and its relationship to possible ore genesis, briefly relates the history of exploration in the area and, finally, assesses the potential for a number of commodities.

GENERAL GEOLOGY

Approximately 10 per cent or 8000 km² of the Athabasca Basin lies within the study area in Alberta. The Athabasca Group is underlain by crystalline basement rocks of the Athabasca Mobile Belt (Burwash and Culbert, 1976) which crop out to the north and south (Fig. 2). Locally, to the west and south, the Athabasca Group is overlain by Phanerozoic carbonates and calcareous sandstones.

BASEMENT GEOLOGY

The basement in the study area has been mapped in outcrop by Godfrey (1970, 1980a, b, and 1984) and in the subsurface by Wilson (1985a, 1986). It comprises a sinuous, linear body of granite gneiss and high-grade metasediments flanked by complex granitoid plutons which locally contain areas of granite gneiss and high-grade metasediments (Fig. 3).

GNEISSES

The main body of granite gneisses and metasediments does not subcrop beneath the Athabasca Basin. However, linear patches of these rocks are present beneath the southwestern portion of the Basin.

The gneisses are heterogeneous, consisting of mafic and felsic gneisses, chlorite schists, aluminous gneisses, amphibolite,

pyroxenite and metasediments, many of which commonly exhibit mylonitic textures. In many places, the rock types are interbanded. They appear to occur beneath the Athabasca Group in linear belts oriented northwest-southeast. They are in part equivalent to the granite gneisses and high-grade metasediments of Godfrey (1980a, b and 1984), and of Langenberg and Nielsen (1982), and also include the mylonitic rocks of Wilson (1985a). The aluminous gneisses may be equivalent to the Peter River Gneiss at Cluff Lake (Tona et al, 1985).

The gneisses probably result from high-grade metamorphism of a mixed suite of sedimentary and volcanic rocks. The aluminous gneisses represent a metamorphosed shale sequence (Pagel and Svab, 1985), so the felsic gneisses may originally have been clastic rocks. Other evidence suggests that some of the gneisses and the mylonitic rocks represent both volcanic and sedimentary parent material (Wilson, 1986).

An Archean age based on a 2500 Ma Rb-Sr date from pegmatoids cutting granitoids which intrude gneisses has been inferred for the granite gneisses north of Lake Athabasca (Baadsgaard and Godfrey, 1967, 1972). Bell (1985) obtained Rb-Sr dates of 1775 ± 55 Ma and 1730 ± 80 Ma on two samples of aluminous pelite from the Peter River Gneiss which crops out in the Carswell Structure. One explanation for the age differences is the possible existence of two successions of supracrustal rocks, one of Archean age (granite gneiss) the other of Aphebian age (Peter River Gneiss). Alternatively, the younger dates at Carswell may reflect a late metamorphic event which affects much older rocks.

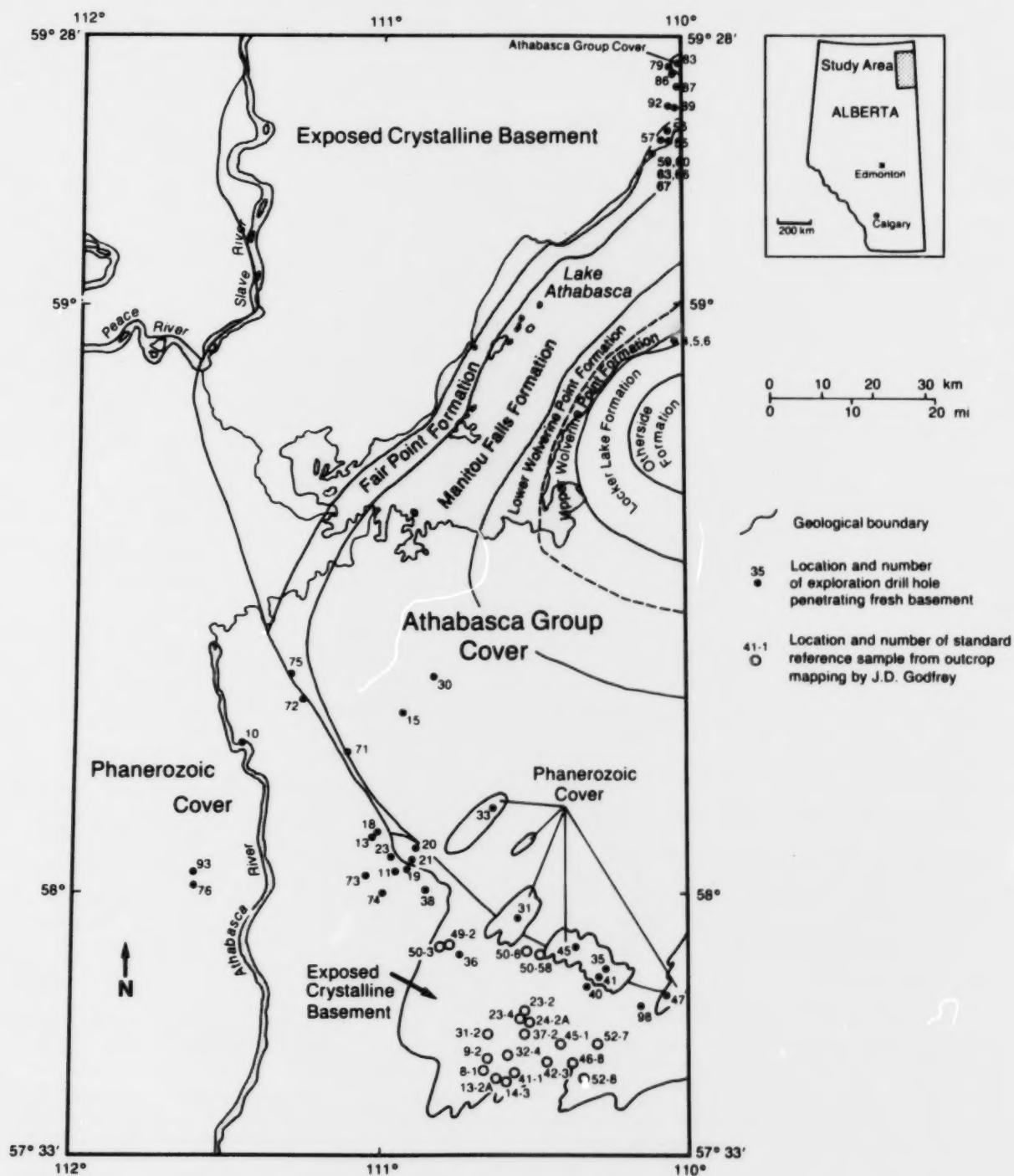


Figure 2. Sketch map of the bedrock geology of the study area showing locations of drill holes which penetrated fresh basement, and of standard reference samples from the Marguerite River outcrop area (after Wilson, 1985b; Godfrey, 1970).

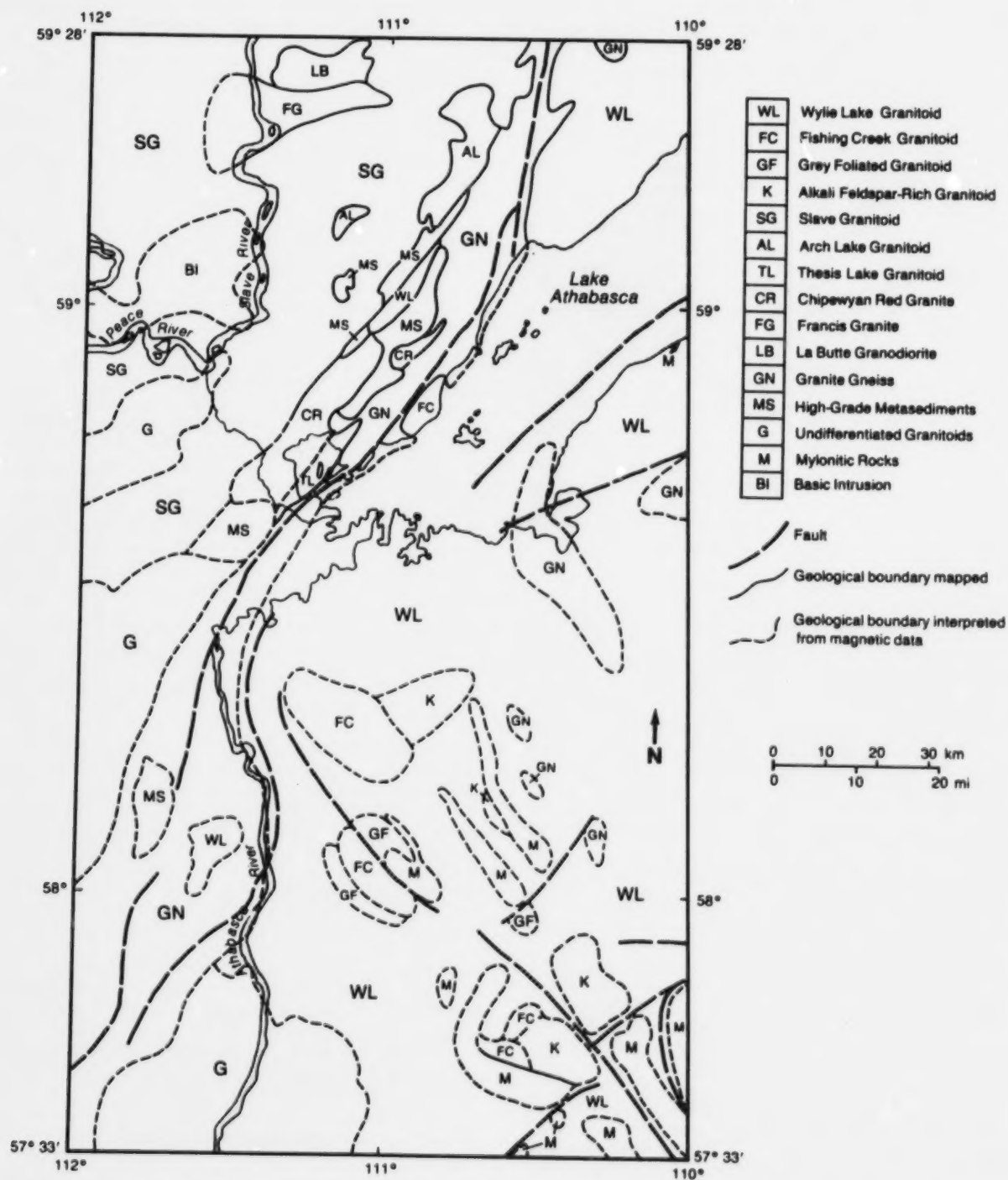


Figure 3. Sketch map of the basement geology in the study area (after Godfrey 1980a, b, and 1984; Wilson 1985b).

GRANITOIDS

Granitoid rocks comprise the bulk of the basement beneath the Athabasca Basin in Alberta. They are part of a complex pluton lying to the east of the granite gneiss belt and extending to the north, south and east of the study area.

The granitoids range in composition from tonalite to granite, and in texture from massive to well foliated. They are predominantly felsic although mafic varieties are locally abundant (the mafic component is generally biotite, but hornblende or pyroxene are present in places). Rarely, the rocks are aluminous. The granitoids beneath the Athabasca Basin in Alberta have been subdivided into four map units on the basis of hand specimen description and alkali-feldspar content (Wilson, 1986). These map units are the Wylie Lake, Fishing Creek, Grey Foliated and Alkali-Feldspar-Rich Granitoids.

The granitoid rocks are part of the Wylie Lake Pluton of Godfrey (1980a, b and 1984) and are probably equivalent in part to the Earl River Complex within the Carswell Structure (Tona et al, 1985). According to Godfrey (1980a, b and 1984), Langenberg and Nielsen (1982), and Goff et al (1986), the granitoids are the product of partial melting of the granite gneisses and metasediments during ultrametamorphism. The Earl River Complex rocks are believed to be the products of anatexis of a meta-arkose sequence (Pagel and Svab, 1985) intercalated with a metamorphosed komatiitic sequence (Bell et al, 1985).

The Wylie Lake pluton is considered to have an origin similar to the other granitoid bodies in Alberta's Precambrian Shield (Godfrey 1980a, b and 1984; Langenberg and Nielsen, 1982; Goff et al, 1986). The Colin Lake Granitoid to the north of the study area has yielded a Rb-Sr date of 1893 ± 6 Ma (Baadsgaard and Godfrey, 1972), and the Slave Granitoid to the west, an age of 1938 ± 29 Ma. Other granitoids, including the Wylie Lake Pluton, show similar ages (H. Baadsgaard, personal communication quoted in Langenberg, 1983). An older generation of granitoids is represented by the Charles Lake Granitoid which crops out north of the study area. This body is cut by pegmatites which have been dated at 2500 Ma (Baadsgaard and Godfrey, 1972).

Rb-Sr ages on quartzofeldspathic gneisses from the Carswell Structure indicate one event at ca. 2000 Ma and another at ca. 1870 Ma (Bell, 1985). Zircons from these quartzofeldspathic gneisses yield U-Pb ages of 2320 ± 20 Ma and 2130 ± 22 Ma. The Rb-Sr ages for the Carswell Structure are compatible with the granitoid ages from the Shield in Alberta and probably represent the period of anatexis and emplacement of the granitoids. The U-Pb zircon ages may represent events relating to the history of the parent (meta)sediments and (meta)volcanics prior to partial melting.

METAMORPHISM AND STRUCTURE

The metamorphic history of the basement has been described by Langenberg and Nielsen (1982), and is schematically presented in Figure 4. Two distinct cycles of metamorphism have been recognized. The first, late Archean in age, affected the metasediments, metavolcanics and granite gneisses, and reached high-pressure granulite-facies metamorphic grade ($P = 7.5 \pm 2$ kbar, $T = 900 \pm 100^\circ\text{C}$).

The second cycle of metamorphism, Aphebian in age, was responsible for partial melting of the granite gneisses and metasediments to produce the granitoids. At its height, it

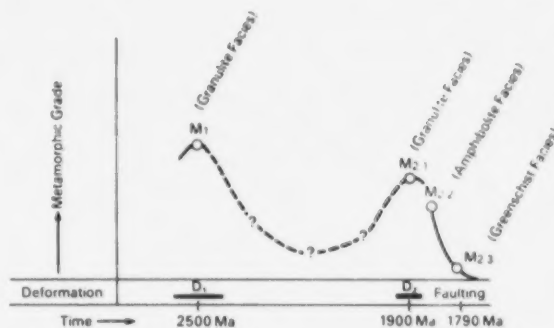


Figure 4. Time scale for the major metamorphic and deformational events affecting the crystalline basement of northeastern Alberta (after Langenberg, 1983).

reached moderate-pressure granulite-facies metamorphic grade ($P = 5.0 \pm 0.7$ kbar, $T = 740 \pm 30^\circ\text{C}$). The suggested age, probably ca. 1900 Ma, is given by the cluster of Rb-Sr dates obtained from the granitoids. Cooling from granulite-facies conditions, through low-pressure amphibolite-facies conditions ($P = 3.0 \pm 0.3$ kbar, $T = 555 \pm 55^\circ\text{C}$) to greenschist-facies conditions ($P = 2$ kbar, $T = 260 \pm 35^\circ\text{C}$) then took place. K-Ar determinations give an average age of 1790 ± 40 Ma (Langenberg, 1983) for the greenschist-facies metamorphism, placing it at the close of the Hudsonian Orogeny. The second cycle is recorded mainly in metasedimentary rocks, but is also recognizable in the granitoids.

Polyphase deformation has been described by Langenberg (1983), who proposed that a deformation phase (D_1 , Fig. 4) which produced tight to isoclinal folds in Archean gneisses was coeval with the first phase of metamorphism. D_1 represents the Kenoran Orogeny at around 2500 Ma.

During the Aphebian, D_2 (Fig. 4) was responsible for the doming of the granitoids and gneisses. It has been dated at 1900 Ma (Hudsonian Orogeny) and correlates with the second phase of granulite metamorphism. Major faults in the area are expressed as shear zones (Watanabe, 1965) and affect most rock units, especially the gneisses. Greenschist facies minerals within fault zones indicate a later Aphebian age for the faulting (Langenberg, 1983). The mylonitic, ductile Aphebian deformation is in some cases overprinted by a late, brittle deformation due to reactivation of the older fault zones.

Two systems of joints are present in the Shield in Alberta (Langenberg, 1983). One system, with one set striking north and the other set striking east, parallels many of the faults in the area. Its age is uncertain. The other system has sets striking northeast and northwest. It is thought to result from the same regional stress field which produced northeast- and northwest-striking joints in the Phanerozoic cover.

COVER GEOLOGY

The Helikian Athabasca Group lies directly upon the crystalline basement. In Alberta, it attains a thickness in excess of 1255 m, and consists predominantly of fluvial clastics and minor interbedded siltstones, mudstones and pyroclastics (Wilson, 1985b). A marine influence is postulated only where the pyroclastics are thickest. The Athabasca Group in Alberta has been subdivided into four formations (Table 1) on the basis of clast size, clay content, pyroclastic content and

sedimentary structure (Wilson, 1985b). This subdivision is based on the formations established by Ramaekers (1979, 1980).

Armstrong and Ramaekers (1985) obtained a Rb-Sr age of 1430 ± 30 Ma on fine-grained sediments from the tuffaceous Wolverine Point Formation. This date may represent the time either of deposition of part of the Athabasca Group, or of early diagenetic devitrification of the tuffs, in which case it provides a minimum age for deposition.

Table 1. Generalized stratigraphy of the Athabasca Group in Alberta.

FORMATION	MAXIMUM THICKNESS (m)	LITHOLOGY
Locker Lake	≥ 205	Medium-grained, pebbly sandstone; pebbles ≥ 10 mm; kaolinite $\geq$ illite Unconformity
Wolverine Point		
Upper member	117	Altered tuffs and medium-grained, friable sandstones; patchy fluorapatite cement; illite $\geq$ chlorite
Lower member	178	Medium-grained sandstone with siltstone ≤ 1 m thick; illite $\geq$ kaolinite $\geq$ chlorite
Manitou Falls	457	Medium-grained, pebbly sandstone; pebbles ≤ 15 mm; kaolinite $\geq$ illite or illite $\geq$ kaolinite
Fair Point	360	Coarse-grained, pebbly sandstone with minor conglomerates; pebbles ≤ 35 mm; kaolinite $\geq$ illite Unconformity

Evidence of tectonism following deposition of the Athabasca Group is sparse on a regional scale. It consists of fracture zones and clay-filled gouges locally cutting the sediments, offsets of the basal unconformity and formational boundaries between drill holes, and the steep dip (55°) of the unconformity where it is exposed at Fidler Point. Extensive deformation in and around the Carswell Structure, a short distance east of the Alberta-Saskatchewan border, suggests that tectonic activity may be widespread in Alberta, where relevant information is sparse. This tectonic activity may be related to the brittle phase of deformation evident in the exposed Shield, or to the forces which formed the Carswell Structure; alternatively, multiple reactivation of older faults and shear zones may have occurred.

Phanerozoic rocks overlap the Athabasca Group at its extreme western edge and in irregular patches along the southwestern edge. They consist of dolomitic sandstones, conglomerates and mudstones with minor vuggy dolomite horizons. These rocks are probably Middle Devonian in age. Evidence that Cretaceous sediments extended as far as the edge of the Athabasca Basin is absent.

The entire study area is blanketed by Pleistocene to Recent, glaciofluvial, glaciolacustrine and eolian deposits (Bayrock, 1972).

ALTERATION

At least five separate alteration events are recognizable in rocks of the Athabasca Basin in Alberta. One has affected

rocks of the Athabasca Group, and the others, basement rocks. Of the four basement-alteration events, one occurred prior to deposition of the Helikian sediments, three after. Alteration in the Athabasca Group cannot currently be correlated with any single diagenetic event in the basement.

ATHABASCA GROUP DIAGENESIS

Rocks of the Athabasca Group have been subjected to a long and complex diagenetic history. Wilson (1985b) has outlined a sequence of alteration events, and described diagenesis affecting permeable sandy units separately from that affecting impermeable tuffaceous units.

Within Athabasca Group sandstones, the most obvious alteration involved silica solution along stylolites and solution seams, and silica precipitation into pore spaces around quartz grains. However, alteration occurred repeatedly both before and after the main phase of silica mobility. Iron has been mobilized at least three times during the history of the group and carbonate twice. Kaolinite has formed at two or three separate times. A major phase of illitization affected the more permeable formations and may have been genetically related to fluid movement from the basement. Minor diagenetic events include the formation of phosphates, tourmaline overgrowths, anatase and cristobalite, as well as the introduction of sulphides and bitumen at a late stage. Many of these events have been preserved only locally, making them difficult to fit into a relative time-scale.

Diagenesis of the tuffs was controlled by their low permeability and their chemistry during devitrification. The most notable event was local development of fluorapatite, which formed prior to compaction and preserves shard textures. Volcanic shards are altered to illite and may be compacted into a groundmass between quartz phenocrysts. Where present, biotite is altered to chlorite. Sulphides, carbonates and altered glauconite grains are locally present.

Alteration within the Athabasca Group is the result of long-lasting, complex diagenesis controlled by the chemistry of the parent sediment and of incoming formational fluids where permeability allowed.

SAPROLITE ALTERATION

Saprolite preserved on the basement rocks beneath the Athabasca Group (Table 2) represents a Helikian surface weathering-zone which may have formed on a regionally more extensive paleoplain (Ambrose, 1964). Remnants of this paleoplain underlie the Athabasca Group (Macdonald, 1980), the Thelon Group (LeCheminant et al, 1983) and the Coppermine Homocline (Kerans et al, 1981). These basins may once have been continuous (Fraser et al, 1970) and the paleoplain may conform to the present exhumed Shield surface (Ambrose, 1964). Fairbridge and Finkl (1980) have suggested that the paleoplain resulted from a worldwide series of events involving prolonged periods of deep chemical weathering interspersed with briefer periods of instability when the weathered zone was stripped off. If this is the case, the sub-Athabasca saprolite represents preservation of part of the chemical weathering profile in low-lying areas of the cratonic surface.

Saprolite is regionally present on the pre-Athabasca Group surface and ranges from 5.5 m to 47 m in thickness. It exhibits a marked, laterally correlative, geochemically distinctive, colour zonation with depth. An upper red, hematitic zone is commonly present, locally capped by a thin, bleached zone.

Table 2. Major events (with probable ages where available) in the geological history of the western end of the Athabasca Basin.

GEOLOGICAL EVENT	RADIOMETRIC AGE
DEVONIAN	
Undivided Middle Devonian	
HELIKIAN	
Diabase Dykes	1310 ± 70 Ma (Armstrong and Ramaekers, 1985)
Athabasca Group	
Locker Lake Formation	
Wolverine Point Formation	
Upper	1430 ± 30 Ma (Armstrong and Ramaekers, 1985)
Lower	
Manitou Falls Formation	
Fair Point	
Saprolite	1632 ± 32 Ma (Fahrig and Loveridge, 1981) 1541 ± 40 Ma 1411 ± 36 Ma (Stevens et al, 1982)
Martin Group	1635 ± 180 Ma (Fraser et al, 1970)
APHEBIAN	
Granitoids (greenschist metamorphism)	1790 ± 40 Ma (Baadsgaard and Godfrey, 1972)
(axatexis)	1893 ± 6 Ma 1938 ± 29 Ma (Baadsgaard and Godfrey, 1972)
ARCHEAN	
Gneiss, chlorite schist, metasediments, mylonites	2500 Ma (Baadsgaard and Godfrey, 1967, 1972)

These are commonly separated from a lowermost green, chloritic zone by a mixed red-green zone.

This zonation bears a striking resemblance to the Hematite, Transitional and Chlorite zones beneath the Thelon Basin (J. Chiarenzelli, personal communication, 1985) and to the regolith developed over pelitic and semipelitic metasediments in Saskatchewan (Macdonald, 1980), although it lacks the prominent white zone of Macdonald's meta-arkose profile. Any one of these zones may be poorly developed or absent at any given location, and the sequence may be complicated by overprinting from later hydrothermal activity.

Major and trace element analyses of whole rock samples from fresh and altered basement are presented in Wilson (1986). Analyses for the saprolite were calculated as percentage gains and losses of a given element assuming aluminum constant. This gives a profile through the saprolite into the fresh basement. Figure 5 presents the mean gain and loss values for all saprolite samples. The trends present in individual profiles (Wilson, 1986) are reflected in the mean values.

All three saprolite zones are strongly depleted in Ca, Na, Mn, Ba and C. Other elements such as Mg, K, Fe, V and Zn show a gradual upwards depletion, and Si, Ti, Pb, Ni, Co, Sr and U are constant or slightly depleted. Arsenic shows an upwards increase, but is present in the fresh rock in such small quantities that this trend may be invalid. Phosphorus shows a gain in the red zone due to the local presence of crandallite-group minerals. The gain in uranium in the green zone is due to a few anomalously high values; it is not a general trend.

These geochemical data convincingly show that the saprolite alteration is a leaching process for most elements. Trends for the major elements match observed petrographic changes through the profile (Wilson, 1986).

The age of the saprolite lies between the age of greenschist metamorphism of the Shield (1790 ± 40 Ma, Baadsgaard and Godfrey, 1972) and deposition of the Athabasca Group (1430 ± 30 Ma, Armstrong and Ramaekers, 1985) (Table 2). Saprolite is absent beneath the Martin Group in the Beaverlodge area of Saskatchewan. This indicates that weathering, assumed to have been regionally developed, occurred after deposition of the Martin Group. Basalts within the Martin Group have been dated at 1635 ± 180 Ma (Fraser et al, 1970). A Rb-Sr date of 1632 ± 32 Ma (Fahrig and Loveridge, 1981) and K-Ar ages of 1541 ± 40 Ma and 1411 ± 36 Ma (Stevens et al, 1982) have been obtained on weathered basement rocks from Saskatchewan. The K-Ar ages were obtained close to uranium deposits and may have been affected by later alteration associated with mineralization.

HYDROTHERMAL ALTERATION

Hydrothermal alteration is present throughout the basement beneath the Athabasca Basin. It is commonly associated with fractures and may affect fresh basement or overprint the earlier saprolite alteration. In general, the hydrothermal alteration is white or cream to pale yellowish green in colour, feldspars having been more-or-less converted to clay. It is indistinguishable from widespread alteration present beneath Devonian carbonates to the west and south of the Athabasca Basin, but may represent at least two distinct phases of alteration.

The crosses on the plots in Figure 5 represent mean gain or loss values for each element in hydrothermally altered samples. For most major and trace elements, the geochemical trend closely matches the trend of the green zone of the saprolite. Both types of alteration thus probably took place under similar conditions. Carbon displays a different trend in hydrothermally altered rock, where it is enriched, from that in the green zone, where it is depleted. The difference in magnesium content which Tremblay (1983) noticed between hydrothermal and saprolite alteration was found to be insignificant for the green zone but was substantial for the red zone.

Hydrothermal alteration in the study area is predominantly a leaching process. It occurred after the formation of the saprolite, and may involve at least two events, one of which occurred after the deposition of Devonian carbonates.

BLEACHED-ZONE ALTERATION

A bleached zone a few centimetres thick is locally present immediately below the sub-Athabasca unconformity. This alteration overprints the red zone of the saprolite. Geochemically the bleached zone is similar to, or continues, the trend of the red-zone alteration. The bleaching is due to the removal of hematite from the red zone.

The bleached zone developed after deposition of the Athabasca Group. It represents local interaction of formation fluids from the Athabasca Group with basement rocks, and may correlate with one of the diagenetic events in the sediments.

ANOMALOUS ALTERATION

Geochemical data outlined anomalous alteration in drill hole 4, situated on the south shore of Lake Athabasca close to the

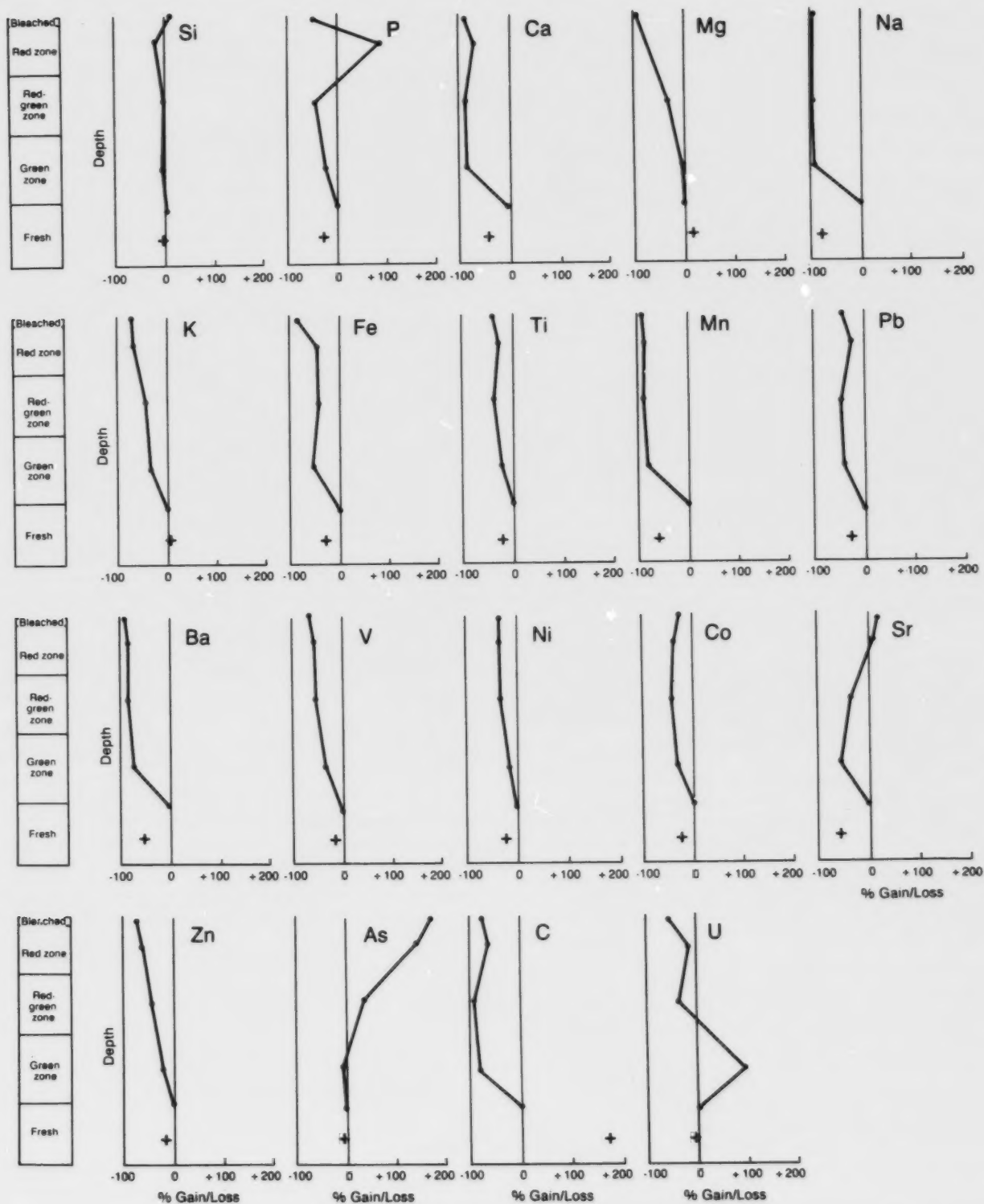


Figure 5. Percentage gain or loss of major and trace elements (mean values) through a typical saprolite profile. Aluminum assumed constant + hydrothermal alteration; N = 10 for bleached zone; N = 35 for red zone; N = 22 for red-green zone; N = 12 for green zone; N = 50 for fresh basement; N = 46 for hydrothermal alteration.

Saskatchewan border. This alteration overprints recognizable saprolite which has formed from a mafic gneissic and granitoid basement, and takes the form of local chloritization.

Percentage gains and losses, assuming aluminum to be constant, are plotted in Figure 6. Anomalous enrichment of Si, K, Ca, Na, Pb, Ni, Ba, Co, Sr, Zn, and U are shown, sharply contrasting with the depletions characteristic of saprolite. Hydrothermal alteration data for the rock types present in hole 4 are similar to equivalent data from elsewhere.

The anomalous alteration postdates the saprolite formation and, probably, the deposition of the Athabasca Group. The process increased, rather than reduced, the concentration of many elements in the original rock.

HISTORY OF EXPLORATION

Exploration for uranium has been intermittent in the western end of the Athabasca Basin since the mid-1960s. Exploration for other commodities has been negligible. No economically viable uranium deposits have been found yet in Alberta, and those in Saskatchewan differ from the deposits at the eastern end of the Basin. Mineral exploration in the western end of the Athabasca Basin in Saskatchewan has concentrated on uranium, and has centred on three main areas:

- 1) along the northern edge of the Athabasca Basin,
- 2) around the Carswell Structure, and
- 3) along the southern edge of the Basin.

In the north, small deposits were found at Maurice Bay, Fond du Lac and Stewart Island. Around the Carswell Structure, a few large and several small deposits have been found. The southern edge of the Basin is a difficult area to work in, having a thick transported overburden and local Phanerozoic cover; exploration here has so far proved unsuccessful.

All the uranium deposits found in the western Athabasca Basin in Saskatchewan have radioactive boulders as a surface expression, and most were discovered by airborne radiometric surveys followed up by ground prospecting. They crop out, or subcrop beneath, thin (less than 20 m thick) overburden. They are not obviously associated with strong linear graphitic conductors, and consequently would have been difficult to find if they had been situated beneath a thick overburden without any mineralized boulder trains.

EXPLORATION IN ALBERTA

The announcement of the discovery of the Rabbit Lake orebody in 1968 sparked interest in the Athabasca Basin in Alberta, and most of the land thought to be underlain by the Athabasca Group was optioned within the following year. However, work on individual permits was minor, limited to airborne reconnaissance with little or no ground follow up. In 1974, Eldorado Nuclear Limited took out permits along what was then considered to be the edge of the Basin. This development led to a new phase of exploration which lasted until 1981.

Eldorado Nuclear Limited (Laanela, 1977; Fortuna, 1979), Norcen Energy Resources Limited (McWilliams and Cool, 1979) and British Petroleum Minerals Limited (Bradley, 1978) extended the southwestern limit of the Athabasca Group considerably farther west than had previously been mapped.

Results obtained by these three companies, insofar as economically viable mineralization was concerned, were disappointing. All anomalies discovered by airborne reconnaissance were, during follow-up work on the ground, found to be features in the Devonian cover or in basement without overlying sandstone. Graphitic horizons in the basement were not traceable beneath the sandstone. Thorium values were everywhere higher than those for uranium, and assays of basement rocks produced maximum values of 10 ppm uranium. Inferred faults which offset the sandstone edge do not show on airborne Input EM or magnetometer surveys, and therefore are not graphitic. They are probably completely healed.

To the north, Uranerz Exploration and Mining Limited (Lehnert-Thiel et al, 1978) undertook extensive exploration and drilling on the northern edge of the basin at Fallingsand and Greywillow Points. Although their results in Alberta were disappointing, they discovered the Maurice Bay deposit in Saskatchewan.

A joint venture headed by Golden Eagle Oil and Gas Limited worked on leases on the south shore of Lake Athabasca at Stone Point and Jackfish Creek (Nelson, 1978). Beneath a thick succession (800m to 1200m) of Athabasca Group sediments, the basement locally exhibited anomalously high Ca, Na, Pb, Ba, Ni, Co, Sr, Zn, U and Au values (Nelson, 1978; Wilson, 1986). In addition to the geochemical anomaly, a 22°C temperature anomaly and very high gamma counts were encountered near the bottom of one hole at Jackfish Creek (W.E. Nelson, personal communication, 1981). Drilling was undertaken on a smaller scale by Flin Flon Mines Limited on Burntwood Island, Esso Minerals Canada Limited east of Old Fort Bay (Brown, 1978), and Chevron Oil and Gas Limited around Agar Lake.

This phase of exploration activity ended in 1981 with the work done by Norcen Energy Resources Limited on an outlier of Athabasca Group rocks which straddles the Alberta-Saskatchewan border east of Burstall Lake.

The introduction of Alberta's new Metallic Minerals Regulations in 1984 has opened up the lands over the Athabasca Basin to further exploration. Permits 6884100001, 6884100002 and 6884120001 were issued to Uranerz Exploration and Mining Limited early in 1985. These were followed up with 5 more permits (6886050002-6) issued in June 1986. The area currently held as permits by Uranerz Exploration and Mining Limited covers approximately 600 km².

POTENTIAL

The prime potential for economic mineral deposits in the western end of the Athabasca Basin is for uranium. However, lead-zinc, gold and phosphate might occur in economically viable quantities.

URANIUM

The existing deposits in the western part of the Athabasca Basin differ in some respects from those in the eastern part. They have a simpler mineralogy, consist of small high-grade pods surrounded by low-grade aureoles, and are more likely to occur in the sandstone. Unlike their eastern counterparts, these western deposits are not strongly associated with linear zones of graphitic pelites.

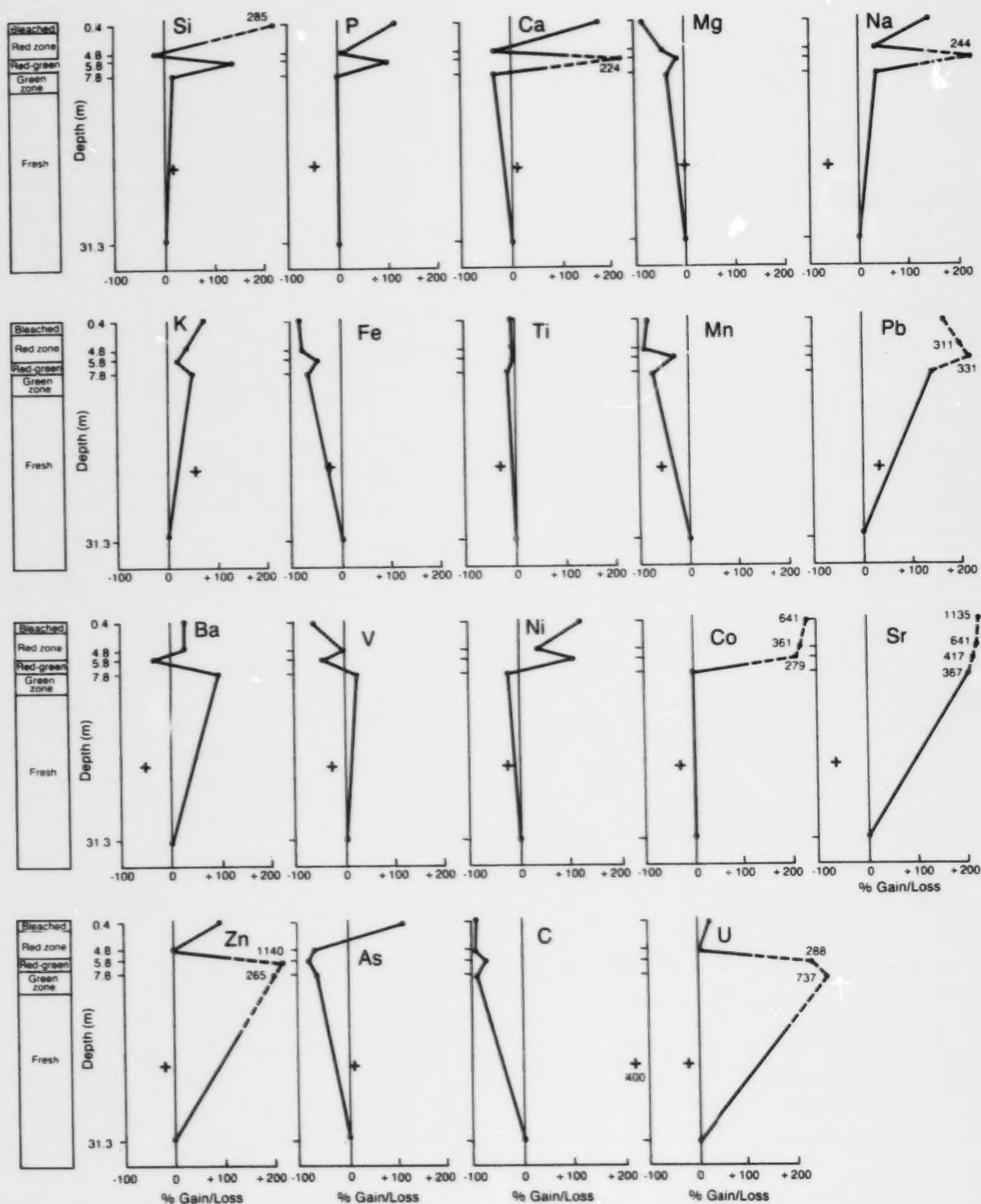


Figure 6. Percentage gain or loss of major and trace elements for anomalous alteration overprinting the saprolite profile in drill hole 4.

At Cluff Lake, four major controls on uranium concentration, all of which were probably in place prior to Athabasca Group deposition, have been proposed (Tona et al, 1985):

- 1) the stratigraphic contact between the Earl River Complex and the Peter River Gneiss,
- 2) the mylonite zone,
- 3) transverse faulting (north and N60°E) through the mylonite, and
- 4) the sub-Athabasca unconformity.

Although graphitic and pyritic rocks of the Peter River Gneiss acted as reducing sites during the concentration of uranium, their presence alone is no guarantee of uranium mineralization.

The Maurice Bay deposit is hosted by both Athabasca Group and basement rocks, and is associated with faults which were active prior to or during Athabasca Group deposition. The deposits at Stewart Island and Fond du Lac are hosted by Athabasca Group rocks and occur in fractures and faults as well as along bedding planes in the sandstone.

Table 3 shows several characteristics of uranium deposits in the western Athabasca Group. The deposits are hosted by both Athabasca Group and basement rocks, and all have a surface expression which can be outlined by prospecting. Basement rock types hosting the mineralization or lying beneath sandstone-hosted deposits consist of pelites, mafic, and felsic gneisses, and rare amphibolites and granitoids. Alteration of the basement is predominantly chloritization, hematization and sericitization with minor tourmalinization and illitization; molybdenum anomalies are locally present. Alteration in the Athabasca Group is only obvious where the mineralization extends up into the sedimentary rocks, and is surrounded by haloes of chlorite, hematite, illite and — locally — carbonate, tourmaline or sulphides. Radiometric age determinations for mineralization are scattered between 800 and 1200 Ma.

The characteristics of the known deposits in the western Athabasca Basin can be used to establish methods of locating hidden deposits. Surficial prospecting methods have been tried over much of the western end of the Basin, so far unsuccessfully in Alberta and south of the Carswell Structure. This probably means that deposits in these areas are buried by thick Athabasca Group rocks or transported overburden so that any surface expression is too subtle to show on a regional search. The western deposits are not associated with well developed graphitic conductors. Hence, had the known deposits lacked surface expression, they would have been difficult to locate using conventional EM geophysics. The two main discovery methods for locating uranium deposits in the Athabasca Basin thus seem to be unsuitable for finding still-hidden deposits in the west, so different approaches need to be tried. This is not to suggest that deposits associated with graphitic conductors are necessarily absent, nor that areas do not exist where locally derived tills contain evidence of basement mineralization.

The basement rock type hosting deposits or underlying deposits hosted by sandstone is gneiss or pelite. Only rarely are granitoid rocks present. Faulting of the unconformity is widely associated with uranium mineralization, and evidence is present — mainly at Cluff Lake — that the presence of mylonites may be significant to ore genesis.

A search for "western type" Athabasca Basin unconformity uranium deposits should therefore commence with detailed mapping of areas of metasedimentary rocks within the predominantly granitoid terrain. This mapping is facilitated by the distinctive geophysical signatures of both the granite gneisses in Alberta and the Peter River Gneiss in the Carswell Structure. In addition, uranium mineralization is related to diapiric doming of the Earl River Complex rocks in the Carswell Structure (Powell et al, 1985). Doming of the granitoids has been recognized in the Shield of Alberta (Langenberg, 1983), so structural mapping of the basement could be used to identify target areas for metasedimentary rocks located on the flanks of domes.

Once these areas of metasedimentary rocks have been mapped, mineralization targets could be more selectively defined by mapping faults which offset the sub-Athabasca unconformity, graphitic zones and mylonite zones. Rock samples for geochemical analysis to detect alteration haloes (caused by potentially economic uranium deposits) in the basement could be obtained by exploratory drilling.

Future discoveries of uranium deposits in the western Athabasca Basin will require more than merely prospecting boulder trains or drilling graphitic conductors. Since areas where deposits may exist within exploitable depths are large, basic geological and structural mapping to delineate potentially favourable areas for further study should initiate exploration programs. Gneisses, metasediments and mylonitic rocks, all possible hosts to uranium mineralization, are present in the faulted terrain beneath the western end of the Athabasca Basin (Wilson, 1985a).

GOLD

No exploration for gold has been carried out in the western end of the Athabasca Basin. However, exploitable gold deposits may exist. Golden Eagle Oil and Gas assayed for gold in rock samples obtained during drilling on the south shore of Lake Athabasca (Nelson, 1978). Their results showed values of up to 0.08 oz. per ton locally within the basement rocks. Unfortunately, the basement at this locality (hole 4, Fig. 1) is beneath 800 to 900 m of Athabasca Group rocks. However, high gold values may also exist where the cover is thinner.

Economic gold deposits in the Athabasca Basin would probably be genetically and spatially unrelated to the Helikian unconformity. Therefore, the possibility of encountering them should be considered throughout uranium-exploration programs.

LEAD-ZINC

The potential for lead-zinc mineralization exists within both the Athabasca Group and the overlying Devonian carbonates. As with gold, exploration for lead-zinc deposits has not been carried out, and what data are available result from uranium exploration.

Galena and sphalerite mineralization occurs in a steeply-dipping fracture system cutting the Manitou Falls Formation in drill hole 7 (Fig. 1). The core is extremely fractured over several hundred metres with mineralization locally developed on fracture surfaces. Analyses of samples collected at 0.3 m intervals from this fractured zone (Nelson, 1978) gave maximum values of 2700 ppm lead and 2320 ppm zinc. The fracture zone's intersection with the sub-Athabasca unconformity forms a prime exploration target. However, in drill hole 7, the unconformity is beneath more than 1255 m of

sediment. The occurrence of galena predating uranium mineralization at the Midwest deposit is taken by Cumming et al (1984) to indicate an increased potential for mineralization in the basal Athabasca Group.

The Devonian carbonates above and to the west of Athabasca Group rocks have potential for lead-zinc mineralization. The carbonates do not crop out, and thick sections of core through them are rare. However, Walker (1981) suggested the presence of "favourable host rock and depositional environment for Pine Point type lead-zinc mineralization" on S.M.D.C.'s permit 6878110002, although no mineralization was encountered.

PHOSPHATE

Phosphates are widespread within the Athabasca Group, and range in composition from fluorapatite to members of the crandallite group (Wilson, 1985c). The only occurrences of possible economic interest are those associated with tuffs of the upper member of the Wolverine Point Formation (Wilson, 1985b). Microprobe analyses of two samples of phosphate from the tuffs (Wilson, 1985b) indicate it to be relatively pure fluorapatite. It has formed as an early diagenetic cement which preserves volcanic textures from compaction. Locally, core appears to consist of 25 to 35 per cent phosphate (visual estimate) over 0.3 m. Somewhere in the Athabasca Basin, phosphate may be sufficiently highly concentrated to warrant extraction.

Table 3. Characteristics of uranium deposits in the western and northern Athabasca Basin.

Deposit	Host rocks	Basement rock type	Alteration (after Curtis, 1986) Basement	Athabasca Group	Main mineralization	Discovery method
Cluff Lake						
D orebody	Athabasca Group, altered basement	Mafic gneiss, granitoid, felsic gneiss, pelite	Pale green chlorite. Graphite removal. Red-green chlorite/hematite.	Dark green chlorite. Pyrite and galena.	1150 ± 25 Ma (Devillers and Nordman, 1974). 1050 ± 30 Ma (Gancarz, 1979).	Airborne radiometry. Prospecting.
N orebody	Earl River Complex	Mafic gneiss, granitoid, felsic gneiss	Pale green chlorite. Argillic alteration. Hematization. Molybdenum halo. Tourmalinization.		1050 Ma (Geffroy, 1972). 900 Ma (Tona et al, 1985).	Airborne radiometry. Prospecting.
Claude orebody	Peter River Gneiss	Pelite	Pale green chlorite. Sericitic and argillic alteration.		1050 ± 65 Ma (Devillers, 1974).	Prospecting. Trenching.
OP orebody	Peter River Gneiss	Pelite	Pale green chlorite. Argillic alteration. Hematization. Molybdenum halo. Tourmalinization.		800 Ma (Gancarz, 1979). 820-890 Ma (Bell, 1985).	Airborne radiometry. Prospecting.
Dominique-Peter orebody	Peter River Gneiss, Earl River Complex, Mylonite	Pelite, mafic gneiss, granitoid	Sericitization. Chloritization.		950-1050 Ma (Bell, 1985). 820-890 Ma (Bell, 1985).	Airborne radiometry. Prospecting. Drilling.
Maurice Bay	Athabasca Group, White Lake Complex	Pelitic gneiss, amphibolite	Dark green chlorite. Quartz-hematite breccia.	Hematite. Illitization.		Lake sediments. Prospecting.
Fond du Lac	Athabasca Group	Meta-arkose, pelite	Sericite. Chlorite.	Hematite. Chlorite. Tourmaline.	1100-1200 Ma (Homeniuk et al, 1980).	Airborne radiometry. Prospecting.
Stewart Island	Athabasca Group	Pelite, quartzite		Carbonate. Chlorite.	418-646 Ma (Fahrig, 1961). 318 and 24 Ma (Anonymous, 1981).	Prospecting.

SUMMARY

A complex series of diagenetic alterations is preserved in the Athabasca Group rocks, as are other, different types of alteration in the underlying basement. Only illitization in the Athabasca Group has been correlated with any degree of certainty to alteration in the basement. The bleached zone in the basement is probably genetically related to fluid flow in the overlying rocks. Three of the four alteration processes in the basement were strong leaching events with broadly similar geochemical signatures. The fourth has been recognized in only one drill hole, where it enriched the affected rock in a number of elements; it may be related to ore genesis.

Exploration to date in the western end of the Athabasca Basin has concentrated on finding the surface expressions of buried uranium deposits. This approach has been strikingly successful at Cluff Lake and the smaller northern deposits, but has yielded poor results in areas where thick transported overburden and thick Athabasca Group rocks appear to obscure possible surface anomalies. In addition, the presence of strong, linear, graphitic conductors is a still-to-be-proven indicator of uranium concentrations this far west, and may not be as successful as to the east.

A different approach is needed for uranium exploration in the western end of the Athabasca Basin. Using the regional geological conditions around known deposits, a model with the capability to predict the location of hidden targets must be developed.

Examination of the known uranium deposits suggests a lithological control upon ore genesis, for all are associated with metasedimentary rocks, mainly pelites. Mylonitic rocks, structural domes and offsets of the unconformity also appear to have exerted genetic control upon mineralization. The first step in exploration should therefore be geological mapping of suitable rock types. Selected areas can then be drilled, and samples of ore geochemically analysed to find alteration haloes.

The easily found uranium deposits in the western end of the Athabasca Basin are known. The potential for other, as-yet-undiscovered deposits is, however, reasonable. New exploratory techniques may have to be developed to realize this potential. Although the mineral of greatest economic interest is uranium, a sharp lookout for gold, lead-zinc and phosphate should be maintained during exploration.

REFERENCES

- Ambrose, J.W., 1964, Exhumed paleoplains of the Precambrian Shield of North America: *American Journal of Science*, v. 262, p. 817-857.
- Anonymous, 1981, The Stewart Island uranium showing, in Canadian Institute of Mining and Metallurgy, Geology Division, Uranium Field-Excursion Guidebook, Sept. 8-13, p. 81-85.
- Armstrong, R.L., and P. Ramaekers, 1985, Strontium isotopic study of Helikian sediments and diabase dikes in the Athabasca Basin, Northern Saskatchewan: *Canadian Journal of Earth Sciences*, v.22, p. 399-407.
- Baadsgaard, H., and J.D. Godfrey, 1967, Geochronology of the Canadian Shield in northeastern Alberta I: Andrew Lake Area: *Canadian Journal of Earth Sciences*, v. 4, p. 541-563.
- Baadsgaard, H., and J.D. Godfrey, 1972, Geochronology of the Canadian Shield in northeastern Alberta II: Charles-Andrew-Colin Lakes area: *Canadian Journal of Earth Sciences*, v.9, p. 863-881.
- Bayrock, L.A., 1972, Surficial geology, Fort Chipewyan NTS 74L: Research Council of Alberta map, scale 1:250,000, with marginal notes.
- Bell, K., 1985, Geochronology of the Carswell area, northern Saskatchewan, in R. Laine, D. Alonso and M. Svab, eds., *The Carswell Structure Uranium Deposits, Saskatchewan: Geological Association of Canada Special Paper 29*, p.33-46.
- Bell, K., A.D. Cacciotti, and J.H. Schnessl, 1985, Petrography and geochemistry of the Earl River Complex, Carswell Structure, Saskatchewan — a possible Proterozoic komatiitic succession, in R. Laine, D. Alonso and M. Svab, eds., *The Carswell Structure Uranium Deposits, Saskatchewan: Geological Association of Canada Special Paper 29*, p. 71-70.
- Bradley, M.D., 1978, 1978 Diamond drill program on quartz mineral exploration permits 229, 230, 231: Alberta Research Council Quartz Mineral Open File 229-U-AF-154.
- Brown, M.G., 1978, Old Fort Bay Exploration — 1978: Alberta Research Council Quartz Mineral Open File 235-U-AF-157.
- Burwash, R.A., and R.R. Culbert, 1976, Multivariate geochemical and mineral patterns in the Precambrian basement of western Canada: *Canadian Journal of Earth Sciences*, v. 13, p.1-18.
- Cumming, G.L., D. Krstic, J.M. Norden, and H. Baadsgaard, 1984, Isotopic composition of lead in galena and Niarsenides of the Midwest deposit, northern Saskatchewan: *Canadian Journal of Earth Sciences*, v. 21, p. 649-656.
- Curtis, L. 1986, Post-Kombolgie alteration at Jabiluka II and its significance with regards to the Athabasca-Alligator Rivers comparison, in T.I.I. Sibbald and W. Petruk, eds., *Geology of Uranium Deposits: Canadian Institute of Mining and Metallurgy Special Volume 32*, p. 231-245.
- Devillers, C., 1974, Datation de l'Echantillon "Claude" par la Methode U/Pb: Commissariat a l'Energie Atomique, Internal Report.
- Devillers, C., and F. Nordmann, 1974, Datation du Mineral Uranifere de Cluff — Premiers Resultats: Commissariat a l'Energie Atomique, Internal Report.
- Fahrig, W.F., 1961, The Geology of the Athabasca Formation: *Geological Survey of Canada Bulletin 68*.

- Fahrig, W.F., and W.D. Loveridge, 1981, Rb-Sr isochron age of weathered pre-Athabasca Formation basement gneiss, northern Saskatchewan, in Rb-Sr and U-Pb isotopic age studies, Report 4 (in Current Research, Part C, Geological Survey of Canada Paper 81-1C), p. 127-129.
- Fairbridge, R.W., and C.W. Finkl, Jr., 1980, Cratonic erosional unconformities and peneplains: *Journal of Geology*, v. 88, p. 69-86.
- Fortuna, P., 1979, Project 508 Northeastern Alberta: Report on winter exploration 1979 Volume 1, Alberta Research Council Quartz Mineral Open File 218-U-AF-146(1).
- Fraser, J.A., J.A. Donaldson, W.F. Fahrig, and L.P. Tremblay, 1970, Helikian basins and geosynclines of the northwestern Canadian Shield, in A.J. Baer, ed., Symposium on basins and geosynclines of the Canadian Shield: Geological Survey of Canada Paper 70-40, p.213-238.
- Gancarz, A.J., 1979, Chronology of the Cluff Lake Area Uranium Deposit, Saskatchewan, Canada (abstract), in International Uranium Symposium on the Pine Creek Geosyncline, N.T., Australia, Extended Abstracts, p. 91-94.
- Geffroy, J., 1972, Donnees Preliminaires sur le District Uranifere du Lac Cluff (Saskatchewan): Cadre Geologique, Petrographique et Parageneses, Amok Internal Report.
- Godfrey, J.D., 1970, Geology of the Marguerite River district, Alberta: Research Council of Alberta map (scale: 1 inch to 1 mile).
- Godfrey, J.D., 1980a, Geology of the Alexander-Wylie Lakes district: Alberta Research Council Earth Sciences Report 78-1, 26 p.
- Godfrey, J.D., 1980b, Geology of the Fort Chipewyan district: Alberta Research Council Earth Sciences Report 77-3, 20 p.
- Godfrey, J.D., 1984, The geology of the Ryan-Fletcher Lakes district, Alberta: Alberta Research Council Earth Sciences Report 84-2, 28 p.
- Goff, S.P., J.D. Godfrey, and J.G. Holland, 1986, The petrology and geochemistry of the Canadian Shield of northeastern Alberta: Alberta Research Council Bulletin 51, 60 p.
- Homeniuk, L.A., R. Bonnar, and R.J. Clark, 1980, The Fond du Lac Uranium Deposit, Saskatchewan: Canadian Institute of Mining and Metallurgy, Toronto Meeting, Ontario, April, v. 73, abstract.
- Kerans, C., G.M. Ross, J.A. Donaldson, and H.J. Goldsetzer, 1981, Tectonism and depositional history of the Helikian Hornby Bay and Dismal Lakes groups, District of MacKenzie, in F.H.A. Campbell, ed., Proterozoic Basins of Canada: Geological Survey of Canada Paper 81-10, p. 157-182.
- Laanela, H., 1977, Summary of report on exploration activities during 1975, 1976, 1977: Alberta Research Council Quartz Mineral Open File 185-U-AF-115(2).
- Langenberg, C.W., 1983, Polyphase deformation in the Canadian Shield of northeastern Alberta: Alberta Research Council Bulletin 45, 33 p.
- Langenberg, C.W., and P.A. Nielsen, 1982, Polyphase metamorphism in the Canadian Shield of northeastern Alberta: Alberta Research Council Bulletin 42, 80 p.
- LeCheminant, A.N., K.E. Ashton, J. Chiarenzelli, J.A. Donaldson, M.A. Best, S. Tella, and D.L. Thompson, 1983, Geology of Aberdeen Lake map area, District of Keewatin: Preliminary Report, in Current Research, Part A, Geological Survey of Canada Paper 83-1A, p. 437-448.
- Lehnert-Thiel, K., J. Rich, and B. Harmeson, 1978, Summary of exploration program — Alberta quartz mineral permits 189, 190, 193, 194: Alberta Research Council Quartz Mineral Open File 189-U-AF-118(4).
- Macdonald, C.C., 1980, Mineralogy and geochemistry of a Precambrian regolith in the Athabasca Basin: unpublished M.Sc. thesis, University of Saskatchewan, Saskatoon, 151 p.
- McWilliams, G., and L. Cool, 1979, Summary of exploration on quartz mineral exploration permits in northeastern Alberta: Alberta Research Council Quartz Mineral Open File 208-U-AF-136(3).
- Nelson, W.E., 1978, Report on the Lake Athabasca Joint Venture - Permits 219, 220, 221, 222, 223, in Alberta Research Council Quartz Mineral Open File 222-U-AF-150.
- Pagel, M., and M. Svab, 1985, Petrographic and geochemical variations within the Carswell Structure metamorphic core and their implications with respect to uranium mineralization, in R. Laine, D. Alonso and M. Svab, eds., The Carswell Structure Uranium Deposits, Saskatchewan: Geological Association of Canada Special Paper 29, p. 55-70.
- Powell, B., E. Koning, and R. Laine, 1985, Geophysical mapping of gneiss domes in the Carswell Structure and their relationship to uranium mineralization, in R. Laine, D. Alonso and M. Svab, eds., The Carswell Structure Uranium Deposits, Saskatchewan: Geological Association of Canada Special Paper 29, p. 201-212.
- Ramaekers, P., 1979, Stratigraphy of the Athabasca Basin, in J.E. Christopher and R. Macdonald, eds., Summary of Investigations 1979, Saskatchewan Geological Survey: Saskatchewan Mineral Resources Miscellaneous Report 79-10, p. 154-160.
- Ramaekers, P., 1980, Stratigraphy and tectonic history of the Athabasca Group (Helikian) of northern Saskatchewan, in J.E. Christopher and R. Macdonald, eds., Summary of Investigations 1980, Saskatchewan Geological Survey: Saskatchewan Mineral Resources Miscellaneous Report 80-4, p. 99-106.
- Stevens, R. D., R.N. Delabio, and G. R. Lachance, 1982, Age determinations and geological studies, K-Ar isotopic ages, Report 15, in Geological Survey of Canada Paper 81-2, p. 33-35.
- Tona, F., D. Alonso, and M. Svab, 1985, Geology and mineralization of the Carswell Structure — a general

- approach, in R. Laine, D. Alonso and M. Svab, eds., *The Carswell Structure Uranium Deposits, Saskatchewan: Geological Association of Canada Special Paper 29*, p.1-18.
- Tremblay, L.P., 1983, Some chemical aspects of the regolithic and hydrothermal alterations associated with uranium mineralization in the Athabasca Basin, Saskatchewan, in *Current Research Part A, Geological Survey of Canada Paper 83-1A*, p. 1-14.
- Walker, T., 1981, S.M.D. Mining Co. Ltd., Wood Buffalo Project — final report on exploration activities: Alberta Research Council Quartz Mineral Open File Report on permits 6878110001 and 6878110002.
- Watanabe, R. Y., 1965, Petrology of the cataclastic rocks of northeastern Alberta: Ph.D. thesis, University of Alberta, 219 p.
- Wilson, J.A., 1985a, The geology of the basement beneath and around the Athabasca Basin in Alberta, NTS 74L and parts of 74M and E: Alberta Research Council Open File Map 85-10.
- Wilson, J.A., 1985b, Geology of the Athabasca Group in Alberta: Alberta Research Council Bulletin 49, 78 p.
- Wilson, J.A., 1985c, Crandallite group minerals in the Helikian Athabasca Group in Alberta, Canada: *Canadian Journal of Earth Sciences*, v.22, p. 637-641.
- Wilson, J.A., 1986, Geology of the basement beneath the Athabasca Basin in Alberta: Alberta Research Council Bulletin 55, 61 p.

A TYPE STRATIGRAPHIC SECTION OF THE ORE ZONE OF A POTASH MINE NEAR SASKATOON, SASKATCHEWAN

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ABSTRACT

A detailed stratigraphic section is presented of the main potash ore zone in the Patience Lake Member of the Prairie Evaporite at Potash Corporation of Saskatchewan Mining Limited, Cory Division. The section, chosen from more than 35 recorded within the mine, is tentatively considered to represent 'normal' conditions within the ore zone. Using clay marker seams and a new classification of potash rock types, the 4.7 m section is subdivided into nine units. Trends in the vertical distribution of K₂O and insolubles are presented. Despite lateral variation in the thickness and lithology, individual units or groups of units can be correlated within the mine.

INTRODUCTION

Despite many years of study (e.g. Schwerdtner, 1964; Wardlaw, 1968; Holter, 1969; Worsley and Fuzesy, 1979), little attempt has been made to investigate systematically the detailed stratigraphy of the main potash ore zones of the Middle Devonian Prairie Evaporite Formation. We present here a measured section from one of the ore-producing zones of the Patience Lake Member (Fig. 1) as a preliminary attempt to standardize the stratigraphy and terminology.

The aim of this study is to establish, first, some generally applicable descriptive rock types and, second, small-scale stratigraphic subdivisions of the typical mining unit. If this is successful, it will provide a means of comparing the economic potash units between the various mines in the area. Within a mine, it should assist in deciding what constitutes normal variation within the mining unit and may provide indicators of anomalous ground (Baar, 1974; Mackintosh and McVittie, 1983) in advance of the mining machine.

The section (Fig. 2) is one of more than 35 logged within the mine of the Potash Corporation of Saskatchewan (PCS) Mining Limited, Cory Division, situated nine kilometres west of Saskatoon. It occurs in an area away from anomalous ground and is considered representative of the normal stratigraphic sequence.

Two main potash levels within the Patience Lake Member are separated by beds of halite. At the Cory Division, these levels have been informally termed the "A-Zone", and "B-Zone" (Fig. 1). The described section represents the productive part of the "A-Zone", the upper of the two zones. Although

labelled differently in other mines, it can be readily recognized by a triplet of clay seams (Unit 9) at the top of the mined potash ore beds. The lowest of these seams, the No. 1 Clay, has been adopted as the general datum within the mine.

METHODS

Sections were measured on mine walls with respect to the datum. Short core samples were collected at vertical intervals ranging from <5 to about 50 cm using a portable drill. Sample splits were analysed semi-quantitatively for mineralogy by X-ray diffraction with reference to prepared standards. The K₂O content of the water-soluble fraction was analysed by ion-specific electrode. The percentage of insolubles was determined as the weight difference after dissolution of the salts.

MINERALOGY AND ROCK CLASSIFICATION

The salts consist mainly of a mixture of halite (NaCl) and sylvite (KCl), with variable amounts of insolubles. Only minor carnallite (KCl·MgCl₂·6H₂O) occurs in the sections examined at Cory Division, even though it is common elsewhere (Wardlaw, 1968; Fuzesy, 1983).

The insolubles occur as "clay seams" variously separating beds of halite and sylvite, as patches within potash ore and interstitially dispersed between grains of various salts. Preliminary X-ray diffraction analyses of the insoluble fractions confirm the results of Mossman et al (1982). The clay minerals are mostly illite, chlorite, septeclorite, smectite and mixed-layer clays. Other minerals include quartz, K-feldspar, hematite, goethite, dolomite, anhydrite and gypsum; the last occurs as small euhedra within halite. Analysis of the

stratigraphy of the insoluble fraction is in progress and results will be presented elsewhere.

As yet, no system has been established for describing the potash ore and associated lithologies at the mine face or in hand specimen. The rock term 'sylvinite' is commonly used to encompass variable mixtures of halite and sylvite. A classification into lithological types is being developed in an attempt to standardize descriptive terminology. Emphasis has been given to utility rather than genetic connotations.

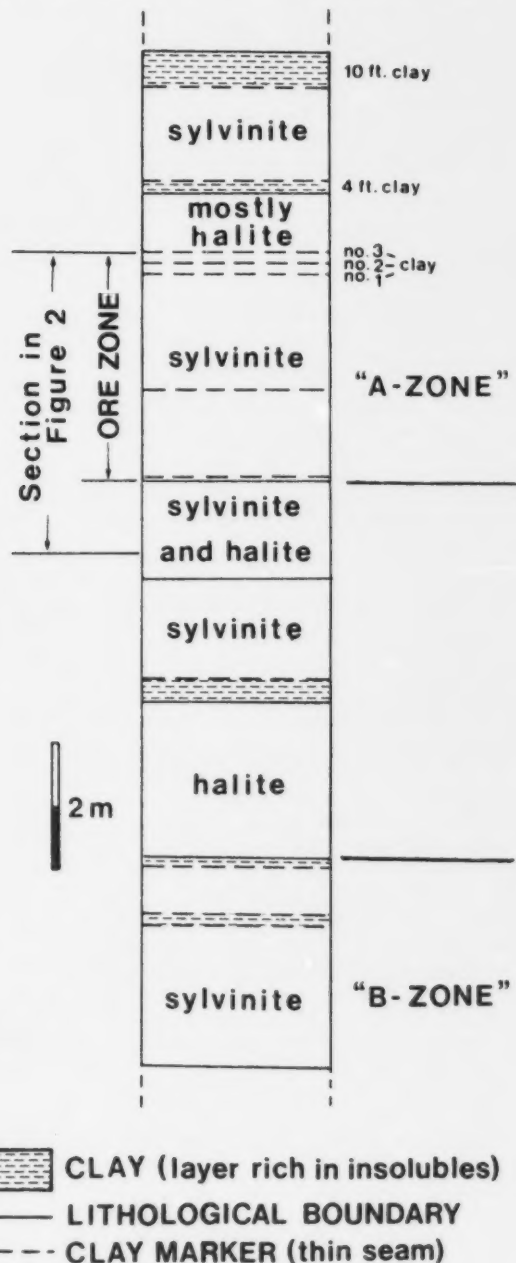


Figure 1. Generalized stratigraphy of a portion of the Patience Lake Member, PCS Mining Limited, Cory Division, showing the main clay seams and the position of the section in Figure 2.

To date, seven broadly defined rock types have been recognized from more than 300 samples examined, informally labelled 'A' to 'G'. As their petrography and genesis are still being studied, no formal names have yet been applied. Their characteristics are summarized in Table 1. The rocks are classified on the basis of composition, colour, translucency, grain or crystal size, texture and the amount and form of insolubles. The terms 'granoblastic' and 'porphyroblastic' are used descriptively. Granoblastic refers here to evaporite rocks that are generally equigranular with interlocking grains, whether the texture was produced as a primary crystal accumulation, or by subsequent overgrowth or recrystallization. Porphyroblastic is used where larger, generally euhedral to subhedral crystals occur within a matrix of smaller grains. In most examples, the porphyroblasts are probably postdepositional but no attempt is made to interpret the textures in terms of precipitation and diagenesis.

STRATIGRAPHIC SECTION

GENERAL

The type section is situated 1800 m west of the Number 1 shaft at the Cory Mine. It extends from the clay seams which define the top of the mining unit, to a 5 cm-thick, brown and grey clay seam 4.9 m lower down (Fig. 2). Normally the thickness of the mined zone is 3.3 m (11 feet), governed by the height of the mining machine. In the vicinity of the type section, the floor has been deepened so that a thicker section is exposed. To take advantage of this, two measured sections within 5 m of one another were combined to produce the type section.

The units were selected on the basis of their being largely composed of one of the rock types (A to G, see Table 1) recognizable throughout much of the mine. Contacts between some units are gradational over thicknesses of 3 to 5 cm; where they coincide with clay seams they may be sharp. The rock-type classification was developed independently of the type section, and rock types do not occur sequentially in order from A to G. Type F is limited to a layer about 3 cm thick in the type section, and type E is absent.

Units 6, 7, and 8 are reasonably consistent over a large area, but the units below unit 6 are variable and less easily traced. Elsewhere, clay seams occur at about the level of units 4 and 5, but these are not sufficiently consistent to be utilized as markers in the same way that the clay seams in Unit 9 are used.

UNIT 1

At the type locality, the base of the section is marked by a brown and greenish grey clay about 5 cm thick. Above it is a 10 cm-thick layer of sylvinite characterized by clusters of orange-red sylvite grains interspersed in colourless and white halite grains giving the rock a patchy appearance. Sylvite grains are generally less than 8 mm across whereas halite grains attain diameters of up to 20 mm. Because of the clustering, grains appear to be larger than they really are. This is typical of G-type rock.

The sylvite is uniformly or patchily coloured in various shades of orange, which may alternatively be confined to grain-rims. The grains are anhedral and interlocking. Small orange grains in the halite may be sylvite remnants. Halite films occur between many sylvite grains.

The colour of the halite is somewhat variable. Colourless grains are most common, but a few areas are dominated by

Table 1. Properties of six rock types from the potash ore zone.

ROCK TYPE	A	B	C	D	F	G
DIAGNOSTIC FEATURES	Thick orange-red rims on many evenly distributed sylvite grains	Pale orange; low content of insolubles	Majority of small (0.5 to 5 mm) grains	Majority of thin red-rimmed sylvite grains	Abundant brown halite	Patchy reddish sylvite
TRANSLUCENCE	Opaque	Low to high	Opaque to moderate	Opaque to low	Opaque to high	Low to medium, patchy
TEXTURE	Granoblastic, porphyroblastic	Granoblastic porphyroblastic	Granoblastic	Granoblastic	Granoblastic, porphyroblastic	Granoblastic
OCCURRENCE	Most common	Common	Minor	Common	Minor	Common
S Grain size	1 to 8 mm	0.5 to 8 mm	0.5 to 5 mm	1 to 12 mm, average 6 mm	0.1 to 5 mm	0.5 to 8 mm
Y L V	granoblastic, 1.5 to 12 mm porphyroblastic	granoblastic, 1 to 18 mm porphyroblastic				
I Grain shape	Subhedral, most anhedral	Anhedral	Anhedral, equant	Anhedral, equant	Anhedral	Anhedral
T Colour	Thick, orange-red to red fringes; clear to cloudy centres	Wispy orange; clear, cloudy	Orange to red	Red rims; clear to cloudy centres	Orange flecks	Orange-red to red
Amount	High	Moderate to high	High	Moderate	Low	Moderate to low
Other	Fractures; insolubles as inclusions	Halite inclusions	Poikiloblastic (?)			Remnant grains
H Grain size	1 to 9 mm	1 to 9 mm	0.5 to 5 mm	1.5 to 12 mm, most 4 to 10 mm	0.5 to 12 mm,	1 to 12 mm, maximum 20 mm
A L I	granoblastic; 2 to 15 mm porphyroblastic	granoblastic; 1 to 18 mm porphyroblastic				
T Grain shape	Anhedral to subhedral	Anhedral to subhedral	Anhedral	Anhedral to subhedral	Most anhedral	Most anhedral
E Colour	Clear to cloudy	Clear to cloudy	Clear to cloudy	Most clear	Brown tint	Clear to cloudy
Amount	Low to moderate	Moderate to low	Low	Moderate	High	Moderate to high
Other	Thin films; inclusions				Insolubles as inclusions	Thin films
I Amount	Variable	Less than 2 per cent	Low	Moderate	Moderate to high	Low to moderate
N S Colour	Mostly green-grey	Green-grey	Green-grey	Green-grey; some brown	Green-grey, brown or both	Mostly green-grey
O L Distribution	Mostly interstitial; inclusions; especially with halite	Inclusions and interstitial; especially with halite	Most form porphyroblasts	Seamlets, inclusions and interstitial.	Variable	Inclusions are numerous; interstitial
U B L E S						



Figure 2. Designated type section of the ore zone (combined sections #3 and #36). Clay seams are indicated by horizontal dashed lines. Insoluble-rich zones are shown by slanted lines in Column I. Clay colours indicated are grey-green (G) or brown (B).

milky grains. The grain size varies from place to place but generally range in diameter from 5 to 15 mm. Most grains are anhedral and a few, subhedral.

Greenish grey insolubles form from one to three per cent of the rock as interstitial material generally associated with halite.

UNIT 2

Unit 2, about 93 cm thick, is dominantly A-type rock with clay seams, each about 1 cm thick (Fig. 2). A-type rock predominates in the main part of the mining zone where potash contents are high. The top 15 cm of this unit falls within the normal ore zone (Fig. 1).

The rock is characteristically brick red, ranging from dark to medium shades. Generally, it is opaque and massive, with an interlocking texture. The rock is mostly orange-red to red sylvite that occurs as porphyroblasts up to 1 cm in diameter and as fine-grained matrix. Some large grains are milky and some are colourless, although most of the colourless grains in the rock are halite. Interstitial clots and films of green clay are common.

The rock is porphyroblastic (grain diameters of 1 to 10 mm) and granoblastic (grain diameters of 1 to 5 mm). The largest grains, 15 to 18 mm across, are mainly halite. In the porphyroblastic varieties, which are the most common, the matrix to the porphyroblasts consists mostly of granular sylvite.

Sylvite grains progressively grade from those with a fairly uniform brick red colour to those with milky or colourless centres and brick-red margins. Grains lacking the red colouration or with the red colour limited to the margins tend to be the largest. Detailed examination of the coloured rims confirms the observation of Holter (1969) that the rims result from accumulation of hematite and goethite.

The largest halite grains are usually clear and colourless, and the smaller ones more milky. Most are subhedral and appear as single grains or clusters isolated in a red sylvite matrix. In some samples, most grains are from 1 to 10 mm across, and in others, from 2 to 18 mm.

The greenish grey insolubles are mainly interstitial, forming discontinuous films around grains where amounts are small. As insolubles increase, they form interstitial clots up to 10 mm in size. Insolubles are commonly associated with halite grains, either along boundaries or as inclusions.

UNIT 3

Unit 3, composed of about 48 cm of the G-type rock, differs from Unit 1 insofar as it contains pale orange sylvite, giving the rock a lighter colour. Parts of the rock dominated by halite appear pale grey with scattered, irregularly shaped patches of orange sylvite. The grains are anhedral and fairly uniform in size, their diameters ranging from 6 to 12 mm. The insolubles are limited to greenish grey interstitial films forming less than two per cent of the rock.

UNIT 4

Unit 4, about 42 cm thick, consists of the main potash-bearing rock type (A-type). In contrast to Unit 2, the insolubles increase towards the top. The top is marked by a 3 cm-thick seam of greenish grey insolubles (clay). The lateral extent of the clay seam and its possible equivalence to other clay seams which occur at about the same elevation are unknown.

UNIT 5

Unit 5, about 25 cm thick, consists of the second major potash-bearing rock type (B-type). The rock varies somewhat in colour but is generally medium- to pale-orange. The texture is mainly granoblastic, and grains are mostly 5 to 15 mm across. The rock differs from A-type in being paler, and equigranular rather than porphyroblastic. Insolubles are sparse and the rock is generally moderately translucent.

Sylvite ranges in colour from medium orange to milky, with wisps of darker orange prevalent near the grain margins. Dark red rims are rare. The interlocking anhedral grains range from 1 to 10 mm in diameter, with exceptional grains as large as 20 mm across. In some places, elongated smaller grains impart a foliation to the rock.

The halite is colourless or milky with rare orange tints. Some of the large grains have cloudy patches, but cloudiness is more common in small grains. The subhedral, interlocking grains are similar in size to those of sylvite but are less variable.

Insolubles in small amounts (less than two per cent) commonly

form small grey-green interstitial masses and films. The insolubles are more abundant where the rock is strongly coloured.

UNIT 6

Unit 6, composed of 135 cm of the main potash-bearing rock type (A-type) of high grade and consistent thickness, forms the core of the ore body. The rock is similar to that of Unit 2, except for variable amounts of greenish grey insolubles throughout. From 5 to 10 cm above the base, the rock is B-type with 1 cm-thick lensoid layers of fine-grained C-type rock (see Table 1). At the base, A-type rock grades downward into B-type rock of Unit 5 (Fig. 2).

UNIT 7

Unit 7, 32 cm thick, consists of the second major potash-bearing rock type (B-type) similar to Unit 5. The content of potash is slightly less than in Unit 6, and of insoluble material, noticeably less.

UNIT 8

A variety of rock types comprises Unit 8, which is about 38 cm thick. At the type section, the central 15 cm consists of B-type rock similar to Unit 7. Above and below, large (diameters from 5 to 10 mm) grains of milky sylvite with distinct, dark red rims characterize the D-type lithology (Fig. 2). Matrix material is limited to small interstitial areas, giving the rock a coarse-grained granoblastic appearance. The dark red colouration results in low translucence.

Most sylvite grains are milky but some are colourless; they have 1.5 mm-wide, dark brick-red rims. Small grains may be coloured throughout, but the colour is mainly patchy. Large grains, mostly equant, are subhedral and anhedral.

Most halite grains are clear, and the remainder are milky to various degrees. The size distribution is similar to that of sylvite, with a tendency to form clusters of a few grains some of which may enclose red sylvite.

Greenish grey insolubles are most common, but in some halite clusters they may be brown. The insolubles occur as interstitial inclusions and clots, generally associated with halite. Where this D-type rock occurs immediately below clay seams, the amount of insoluble material increases to ten per cent from the normal one to two per cent.

UNIT 9

Unit 9, marking the top of the mining interval, is characterized by three clay seams separated by sylvite-bearing rock. The unit is variable, particularly in the nature of the intervening salts. The lowest clay seam at the type section, from 3 to 9 cm thick, is composed of three layers of insolubles, each 1 to 2 cm thick. Fine-grained sylvite, typical of C-type rock (see Table 1), occurs in the lower part of the clay seam whereas A-type rock occurs in its higher part (Fig. 2). Above the lowest clay seam is an 18 cm-thick layer of orange B-type rock grading upward into G-type (5 cm thick) which grades, in turn, into insoluble-rich brown halite (F-type rock, also 5 cm in thickness). This sequence is gradationally overlain by the 3 cm-thick, brown, middle clay seam (Fig. 2). The upper clay seam consists of greenish grey insolubles (3 cm thick) separated from the middle clay seam by a 6 cm thickness of A-type rock, which also overlies the upper clay seam and extends upwards past the top of the mined wall (Fig. 2).

CORRELATION

Units 1 to 9 can be correlated with other sections with variable degrees of success. Figure 3 shows the lithological correlation between the designated type section and three other sections elsewhere within the mine, using the lowest clay seam of Unit 9 as the datum. Some variation exists in the thickness of the units and in the rock type, but most units can be recognized within a given section and are mappable. In places, individual units cannot be traced but groups of units (e.g. 3 to 5) are distinguishable.

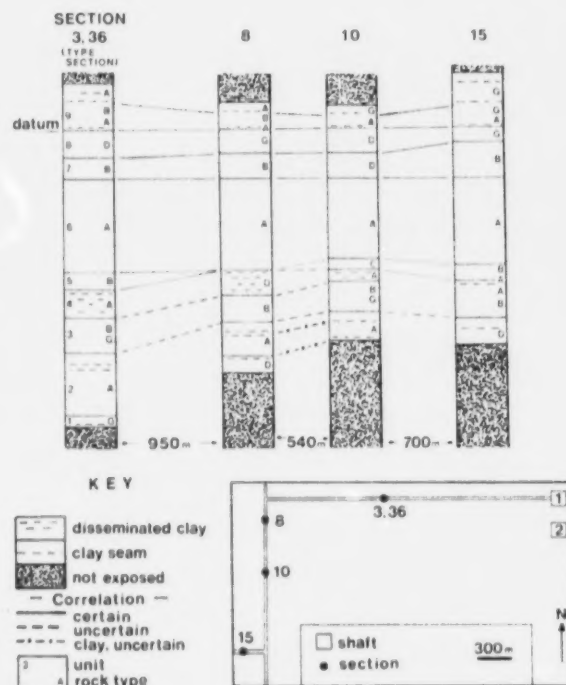


Figure 3. Correlation of the type section with three other sections within the mine at Cory Division. Inset shows the relative positions of the sections within the mine.

CONCLUSIONS AND FUTURE DIRECTIONS

Using a simple classification of rock types, preliminary study has shown that the potential exists for subdividing the potash ore zone into lithological units for purposes of correlation and for improved characterization of the ore body. Lateral variations in the thicknesses and rock types within the defined units occur, but most are mappable, individually or in groups, at least within the limits of a single mine.

The next phase of this study will attempt to extend the scheme, which can now only be regarded as provisional, to other mines and core sections to test its viability. Having established a standard section thought to represent 'normal' conditions, the stratigraphic, mineralogical and geochemical changes associated with proximity to anomalous ground will be investigated. The variations in rock types and stratigraphy will be studied to help determine the genesis of the potash ores and the origins of the anomalies.

We expect that the stratigraphy and rock classification scheme will require revision in the light of future studies.

REFERENCES

- Baar, C.A., 1974, Geological problems in Saskatchewan potash mining due to peculiar conditions during deposition of potash beds, *in* A. H. Coogan, ed., Fourth Symposium on Salt: Northern Ohio Geological Society, Cleveland, p. 101-118.
- Fuzesy, L.M., 1983, Petrology of potash ore in the Middle Devonian Prairie Evaporite, Saskatchewan, *in* R.M. McKercher, ed., Potash Technology: Pergamon, Toronto, p. 47-57.
- Holter, M.E., 1969, The Middle Devonian Prairie Evaporite of Saskatchewan: Saskatchewan Department of Mineral Resources Report 123, 134 p.
- Mackintosh, A.D., and G.A. McVittie, 1983, Geological anomalies observed at the Cominco Ltd. Saskatchewan potash mine, *in* R.M. McKercher, ed., Potash Technology: Pergamon, Toronto, p. 59-64.
- Mossman, D.J., R.N. Delabio, and A.D. Mackintosh, 1982, Mineralogy of clay marker seams in some Saskatchewan potash mines: Canadian Journal of Earth Sciences, v. 19, p. 2126-2140.
- Schwerdtner, W.M., 1964, Genesis of potash rocks in the Middle Devonian Prairie Evaporite Formation of Saskatchewan: American Association of Petroleum Geologists Bulletin, v. 48, p. 1108-1115.
- Wardlaw, N.C., 1968, Carnallite-sylvite relationships in the Middle Devonian Prairie Evaporite Formation, Saskatchewan: Geological Society of America Bulletin, v. 79, p. 1273-1294.
- Worsley, N., and A. Fuzesy, 1979, The potash-bearing members of the Devonian Prairie Evaporite of southeastern Saskatchewan, south of the mining area: Economic Geology, v. 74, p. 377-388.

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THE USE OF STABLE ISOTOPES TO DETERMINE THE SOURCE OF BRINES IN SASKATCHEWAN POTASH MINES

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ABSTRACT

Recent mine floods at the International Minerals and Chemical Corporation K-2 Mine and the Potash Corporation of Saskatchewan Mining Limited, Rocanville Division, have shown the need to identify accurately the source of mine-water leaks in order to undertake proper preventative or remedial action. Chemical compositions of the waters are inadequate as tracers of leaks because:

- 1) the erroneous assumption is made that the concentrations of at least some of the elements do not change during migration of the fluids,*
- 2) interpretation of the significance of chemical composition data relies largely on results from experimental data, and*
- 3) chemical compositions are greatly altered by passage through the Prairie Evaporite Formation.*

Stable isotopes of oxygen and hydrogen are considered conservative elements of water. Within a basin the δD and $\delta^{18}O$ values of pore waters typically increase with depth because of increasing influence of connate waters. Thus, the water in each aquifer within the basin generally has a characteristic isotopic composition which, when compared to the isotopic composition of the floor or leak waters, allows an identification of the brine source irrespective of other changes in chemical composition of the water during migration.

Results indicate that the oxygen and hydrogen isotopic compositions of waters are valid tracers and that this technique can be used to map the flow of water between formations.

INTRODUCTION

Since potash mining began, water leaks have been a major concern. In Saskatchewan, they have created severe problems ever since the first mine shafts penetrated the Mannville Group aquifers (Fuzesy, 1982). Subsequent major leaks include that at the Cominco mine (Prugger, 1979) and recent mining-level floods at International Minerals and Chemical Corporation (IMC) K-2 Mine and the Potash Corporation of Saskatchewan (PCS) Mining, Rocanville Division. The recent loss of a Russian potash mine due to flooding reflects the ultimate severity of water leaks in potash deposits.

Knowledge of the source of the brines is essential in undertaking proper preventative or remedial action. In the past, determination of the origin of the inflowing brine has been interpreted largely from chemical composition of the brine. This method is, however, unreliable because brine

compositions are radically altered by the brines' interaction with evaporites during migration to the mining level. Stable isotopic composition of the waters has been proposed as a more satisfactory indicator of the sources of brines leaking into the potash mines.

In the present study, stable isotopes of hydrogen and oxygen were used to compare water leaking at the mine levels with waters collected from strata above the mining levels. Samples were taken from PCS Mining mines at Cory, Allan, Lanigan and Rocanville (Fig. 1). Samples were collected from sites within the mine shafts and from leaks at mining levels (Fig. 2), except the Lanigan shaft which was too dry to sample. Samples were analysed for D/H, $^{18}O/^{16}O$, Cl, Na, K, Ca, Mg, Br, I, F, pH, alkalinity and density. The chemical components, although not discussed at length in this paper, were analysed in order to study brine composition, and to have a basis for comparison with previous work.

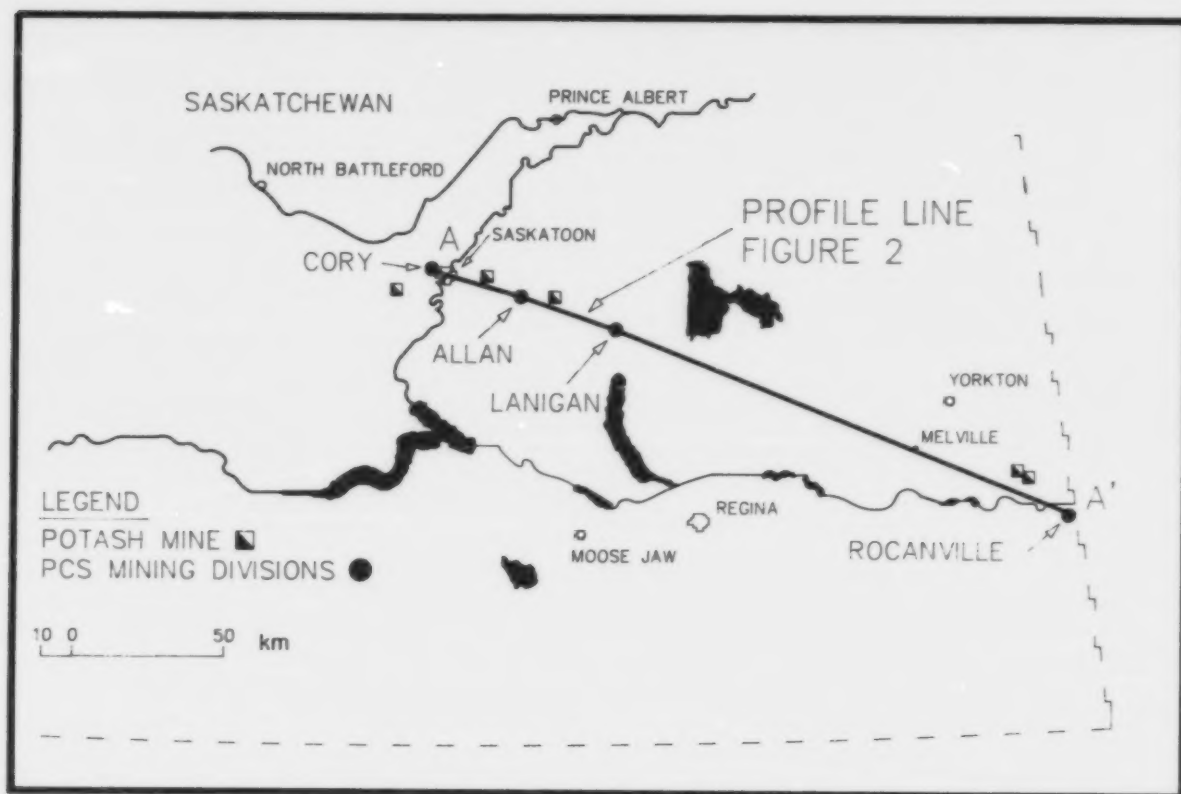


Figure 1. Location map.

GEOLOGICAL SETTING

Potash deposits of economic interest occur in the upper 70 m of the Middle Devonian Prairie Evaporite Formation within the Elk Point Basin at depths of around 1,000 m below surface. Four potash-bearing members are, in descending stratigraphic level: the Patience Lake, Belle Plaine, White Bear and Esterhazy Members (Fig. 2). The Patience Lake Member is mined at the Cory, Allan and Lanigan mines and the Esterhazy Member is mined at Rocanville. The geology of the Prairie Evaporite Formation has been described by Holter (1969) and Fuzesy (1983).

The Prairie Evaporite Formation is underlain by the dolomitic Winnipegosis Formation which has an irregular topography created by reefs and reef-like mounds. The movement of fluids through the Winnipegosis is considered to control local salt dissolution within the evaporite sequence (Gendzwill, 1978). The Prairie Evaporite Formation is overlain by the Second Red Bed Member of the Dawson Bay Formation. The Dawson Bay is the first of a series of Upper Devonian cyclic deposits of limestone, dolomite and evaporites which include the Dawson Bay, Souris River, Duperow and Nisku Formations (Fig. 2). Additional Upper Devonian and Mississippian strata occur in Rocanville area and Jurassic rocks are present in the Allan and Lanigan areas. These sequences are overlain unconformably by the Lower Cretaceous Mannville Group and by a younger section of Cretaceous shales, all capped by Pleistocene glacial deposits and recent sediments (Fig. 2).

The Mannville Group at the base of the Cretaceous contains many porous and permeable sands and forms a large regional aquifer. Formational-fluid movement between the Mannville Group and the Dawson Bay Formation is thought to be continuous (Dunn, 1982). A large fluid system is capped by the relatively impervious Cretaceous shales and is sealed at the bottom by the impervious Prairie Evaporite Formation and the salt-plugged Dawson Bay Formation.

Formational fluids within the basin flow horizontally and vertically. Recharge by meteoric waters occurs at the Central Montana Uplift; this recharge occurred during the latest glaciation and continues to the present times. Direction of fluid flow is largely north to northeast (i.e. towards the formational intersections with the erosional surface). Interformational, or vertical flow, is largely controlled by fractures and by collapse structures caused by the periodic dissolution of the Prairie Evaporite.

In the basin, salinity of formational waters generally increases with depth, even where evaporites are absent. Mechanisms proposed to explain this observation include the complete dissolution of evaporites, brine density flow and membrane filtration. A non-uniform increase in salinity occurs when fluids moving through the formations intersect an evaporite sequence.

The original salinity of the brine within each formation is invariably altered by solution of the evaporite as shown by

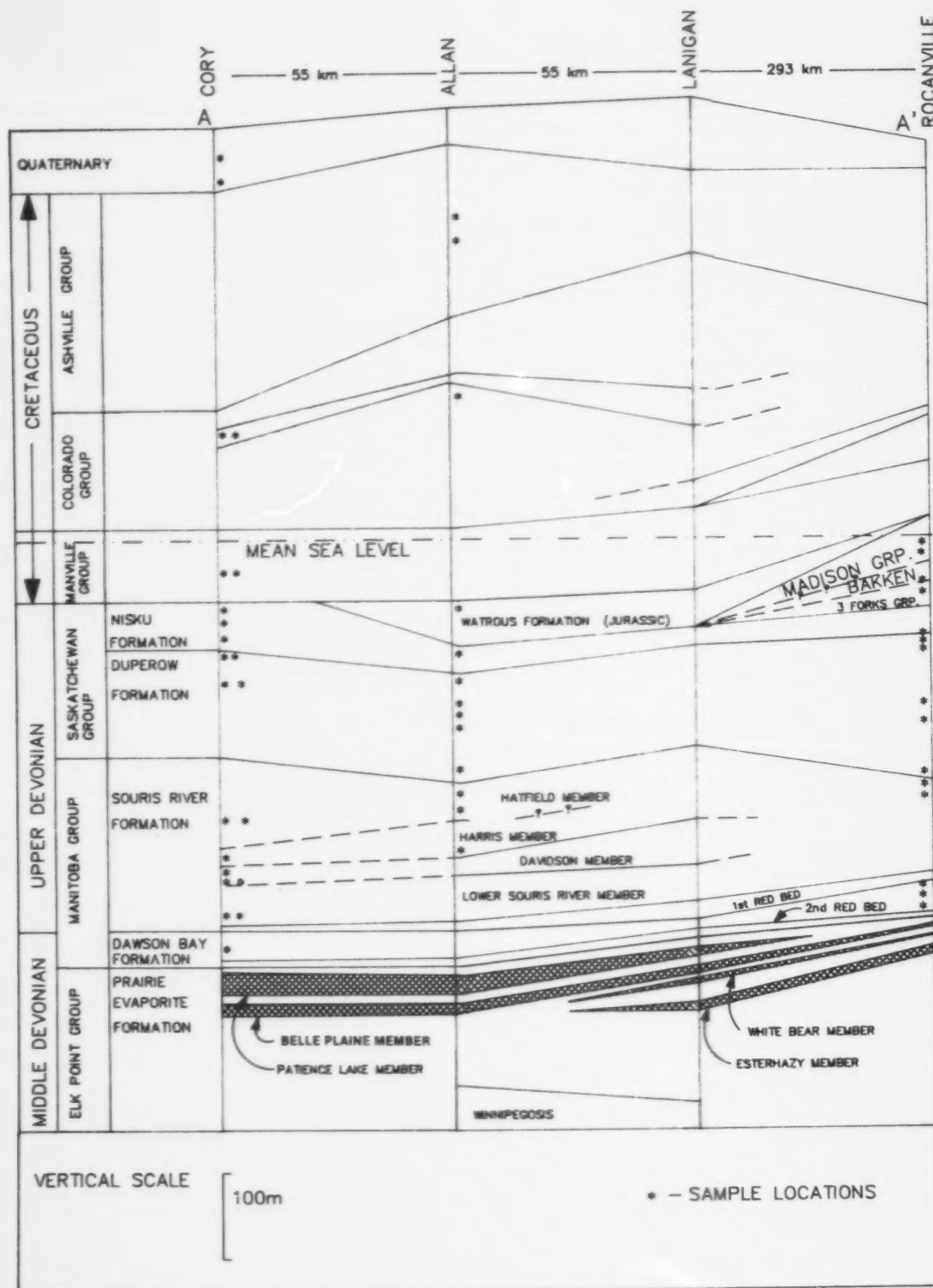


Figure 2. Stratigraphy at the PCS Mining mines in Saskatchewan.

samples collected from the mine shafts or the mining levels. For this reason the dissolved components in the brine are changed in concentration. However, stable isotopes of the water are conservative elements because of:

- 1) the large reservoir of hydrogen and oxygen which exists in the water itself, and
- 2) the relatively slow exchange of stable isotopes between waters and rocks at low temperatures.

Consequently, stable isotopic compositions were chosen for determination of the brine sources.

STABLE ISOTOPES

Water is composed of hydrogen and oxygen which have two and three stable isotopes, respectively. Relative global abundances are reported in Table 1.

Table 1. Stable isotopes of hydrogen and oxygen (Faure, 1977).

Element	Stable Isotope	Global abundance (per cent)
Hydrogen	^1H	99.985
	^2H or D (Deuterium)	0.015
Oxygen	^{16}O	99.756
	^{17}O	0.039
	^{18}O	0.205

The mass of a given sample of water depends upon the isotopic composition of the water molecules. A water molecule of $^1\text{H}_2^{16}\text{O}$ has a mass of 18 whereas a water molecule of D_2^{16}O has a mass number of 22. The isotopic composition of waters is reported as the D/H or $^{18}\text{O}/^{16}\text{O}$ in the sample relative to these ratios in standard mean ocean water (SMOW). These variations normally are small and are reported as delta values (δ) in units of per mil, for example:

$$\delta^{18}\text{O} = \left[\frac{(^{18}\text{O}/^{16}\text{O})_{\text{sample}}}{(^{18}\text{O}/^{16}\text{O})_{\text{SMOW}}} - 1 \right] \times 1,000$$

The vapour pressure of water varies inversely with the mass number; that is, the lower the mass number the higher the vapour pressure because water molecules with lower mass numbers are more stable in the vapour phase than are water molecules with heavier mass numbers. Fractional distillation occurs as water goes through repeated evaporation and precipitation during the meteoric water cycle. Evaporating water is depleted in heavier isotopes and condensing water is enriched in the heavier isotopes. The depletion-enrichment occurs in a regular way with respect to the starting composition of waters. Because the isotopic composition of meteoric water during distillation-evaporation is determined by the mass-difference between the H and D atoms and the ^{16}O and ^{18}O atoms, the δD and $\delta^{18}\text{O}$ values of meteoric waters are always proportional (i.e. $\delta\text{D} = [8 \times \delta^{18}\text{O}] + 10$).

The partitioning of stable isotopes of water among various phases is dependent on both temperature and the vapour

pressure of the water: so that the isotopic composition of precipitation (rain or snow) becomes a function of latitude, altitude and climatic conditions. In addition, as water is removed from a cloud as it passes from the oceans to the continents, the remaining water in the cloud becomes increasingly depleted in the heavy isotopes. Meteoric water in Saskatchewan is very depleted in ^{18}O and D relative to seawater because of latitude, cool climate and distance from the ocean. This evolution of the δD and $\delta^{18}\text{O}$ values in precipitation on a global basis is represented by the meteoric water line (MWL) depicted in Figure 3.

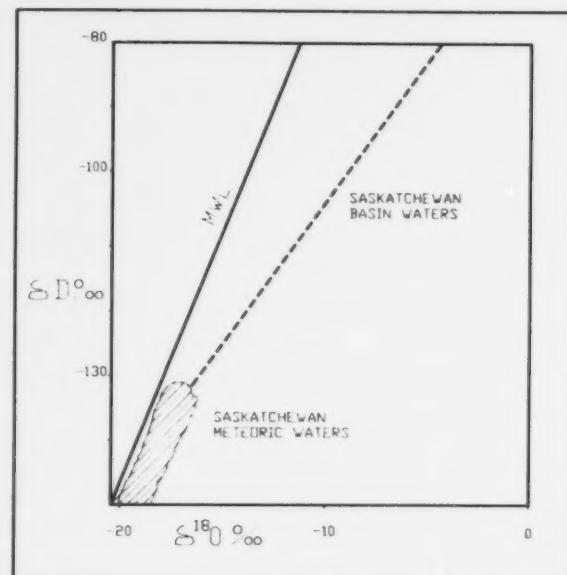


Figure 3. δD o/oo versus $\delta^{18}\text{O}$ o/oo.

When meteoric water enters the ground, fractional distillation is no longer effective and ratios of the stable isotopes are altered only as a result of exchange with host rocks. This exchange affects only the oxygen isotopes in the water because of the large reservoir of oxygen in rocks, but the effect can only be measured after millions of years of contact. In Saskatchewan, the median value for meteoric water is approximately -150 for δD and -20 for $\delta^{18}\text{O}$. These values, however, vary over a small range due to changes in seasons and precipitation patterns. These values are not believed to have altered significantly since the Pleistocene glaciations.

Waters presently in sedimentary basins consist largely of post-glacial meteoric waters which have displaced or mixed with pre-existing basin waters (Clayton et al, 1966). The δD and $\delta^{18}\text{O}$ values within a basin have been shown to increase with depth in a reasonably uniform manner, and each geological basin develops a unique δD vs $\delta^{18}\text{O}$ trend (Hitchon and Friedman, 1979). Schwartz et al (1981) noted that the basinal trend could be generated by stacking values of individual aquifers. Therefore, δD and $\delta^{18}\text{O}$ values increase downward in a given vertical profile and with distance from source within a given aquifer. Schwartz et al (1981) also noted that values of the stable isotopes vary with the flow rates within an aquifer. In a vertical section, δD and $\delta^{18}\text{O}$ values of waters may differ from the general uniformity of the enrichment trend

with depth by having lower values where the formation is flushed more thoroughly and higher values where the fluid flow is more restricted.

The main mechanism by which δD and $\delta^{18}O$ values decrease with decreasing depth is the mixing of meteoric waters with isotopically distinct formation waters. The formational water may be true connate water or water which has resided long enough in the basin to become ^{18}O rich due to reactions between water and rocks. For recent waters, reactions between water and rocks probably contribute a small amount of heavier isotopes to the water due to the slow reaction of hydrogen with clays and of oxygen with carbonates and silicates.

If water depleted in D and ^{18}O is found below an aquifer exhibiting normal isotopic increases with depth, some major disruption in the flow pattern has occurred. The flow pattern has been "short circuited", allowing isotopically lighter water to enter the formation. Processes that permit the decrease of δD and $\delta^{18}O$ with depth are rare.

Short circuiting in the Elk Point Basin is likely caused by the vertical movement of fluids through collapse structures and related features. Collapse structures form when fluids dissolve and periodically remove portions of the Prairie Evaporite with the subsequent collapse of overlying formations (Christiansen, 1971; Christiansen et al, 1982; DeMille et al, 1964; Bishop, 1974; Parker, 1967). Dissolution at depth may be caused by the driving of undersaturated waters by a brine density flow mechanism (Anderson and Kirkland, 1980). The collapse structures allow the waters to follow a path they would not normally take; they allow less saturated, isotopically lighter fluids to enter lower formations.

RESULTS

The data collected to date have been plotted as δD and $\delta^{18}O$ values (Figs. 3, 4 and 5). Generally, the values increase with depth as expected. Some minor variations exist but they are within the ranges expected due to different formational flow rates.

CORY AND ALLAN DIVISIONS

Values of δD and $\delta^{18}O$ increase with depth in a normal manner to the mining levels. At Cory Division, both values decrease slightly in waters of the Duperow Formation (Figs. 4 and 5) — this may be due to a faster formational flow rate or to a more permeable formation so that the Duperow waters are less isolated from mixing with meteoric waters.

Isotopic compositions of water samples from the mining levels at both localities indicate that the majority of water leaking into these mines originates either from the overlying Dawson Bay Formation or from water trapped in the salt. Evidence that some of the leaks result from short circuiting of shallower aquifers is currently limited.

LANIGAN DIVISION

No water samples were available from the Lanigan shaft. Assuming that the waters in formations above the Lanigan Mine have similar values to those above the Cory and Allan Mines, the isotopic compositions of water leaking into the mine are compatible with an origin from shallower aquifers than the Dawson Bay, such as from the Souris River Formation (Fig. 5).

ROCANVILLE DIVISION

Analysis of data from the Rocanville Mine is more complex. Water samples collected from the mine shaft show normal increases in δD and $\delta^{18}O$ values down to the mine level. At

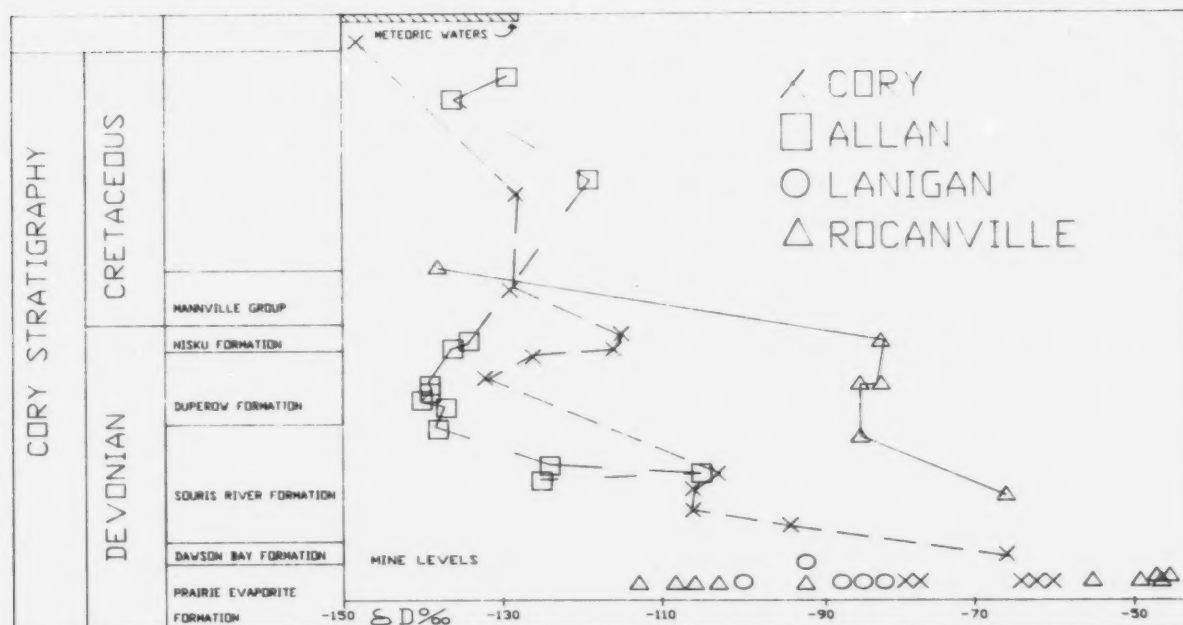


Figure 4. δD versus depth.

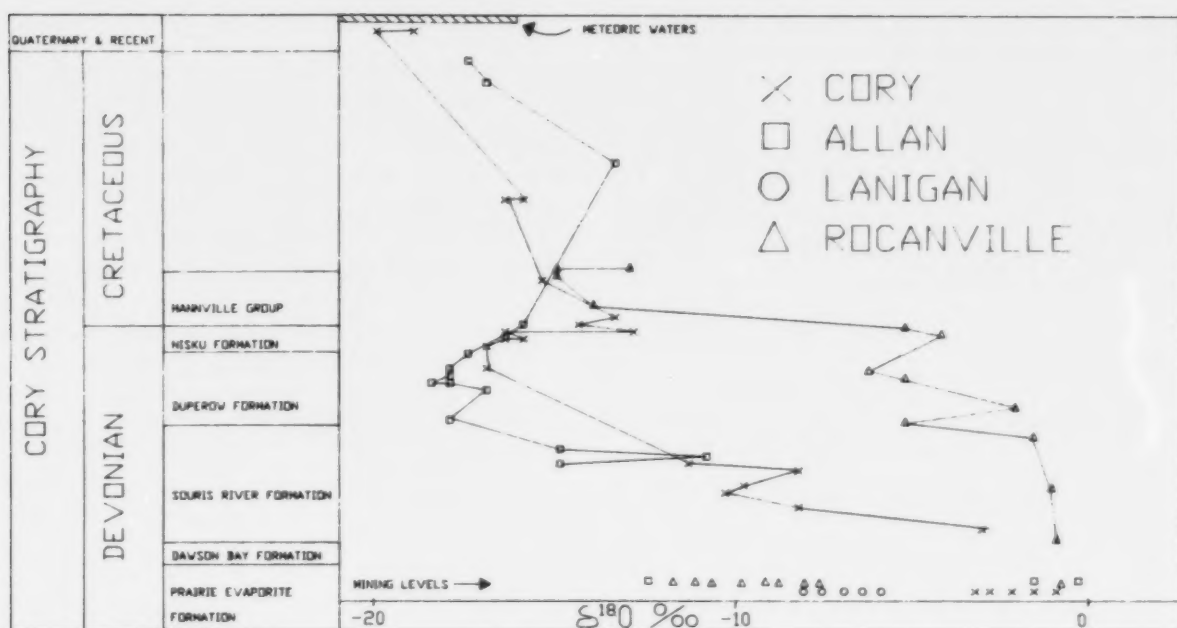


Figure 5. $\delta^{18}\text{O}$ versus depth.

the mining level, the data form two clusters (Figs. 4 and 5), one indicating fluids with isotopic compositions similar to those in the Dawson Bay, the second having much lower values. Water with the low values ($\delta^{18}\text{O}$ of -12 to -8 and δD of -110 to -95) compare most closely with the values obtained from waters of the Mannville Group (Blairmore) or the Nisku Formation.

DISCUSSION

Waters at the Cory and Allan Divisions appear to be normal through to the brines encountered on the mining levels. Any leak in these mines should be monitored in case short circuiting of the formational fluids from shallower aquifers takes place. Mine-level brines in these two mines are unlikely to cause a serious flooding problem because they are in approximate chemical equilibrium with their surroundings.

Rocanville and Lanigan, however, because of the presence of waters from shallower aquifers at the mining level, should be monitored continually as any flooding is potentially more serious. The absence of short-circuited water in the shaft profile at Rocanville is encouraging and indicates that the observed short circuiting is not pervasive. At Rocanville, water sampling from the Mannville and lower formations should be continued in order to determine whether or not the regional flow regime has changed significantly due to the nearby IMC K-2 flood problem.

CONCLUSIONS

Continued isotope-monitoring programs may allow detection of changes in the local flow regimes around potash mines and evaluation of potentially hazardous water flow. A change to short-circuited water is a matter of great concern. A more widespread sampling program involving stable isotopes would greatly increase the knowledge of formation-fluid movement.

REFERENCES

- Anderson, R.Y., and D.W. Kirkland, 1980, Dissolution of salt deposits by brine density flow: *Geology*, v. 8, no. 2, p. 66-69.
- Bishop, R.A., 1974, Hummingbird structure, Saskatchewan, single vs. multiple stage salt solution collapse, in G.R. Parslow, ed., *Fuels: a geological appraisal: Saskatchewan Geological Society Special Publication 2*, p. 179-197.
- Christiansen, E.A., 1971, Geology of the Crater Lake collapse structure in southeastern Saskatchewan: *Canadian Journal of Earth Sciences*, v. 8, p. 1505-1513.
- Christiansen, E.A., D.J. Gendzwill, and W.A. Meneley, 1982, Howe Lake: a hydrodynamic blowout structure: *Canadian Journal of Earth Sciences*, v. 19, p. 1122-1139.
- Clayton, R.N., I. Friedman, D.L. Graf, T.K. Mayeda, W.F. Meents, and N.F. Shimp, 1966, The origin of saline formation waters, 1: Isotopic composition: *Journal of Geophysical Research*, v. 71, no. 16, p. 3869-3882.
- DeMille, G., J.R. Shouldice, and H.W. Nelson, 1964, Collapse structures related to evaporites of the Prairie Evaporite Formation, Saskatchewan: *Geological Society of America Bulletin*, v. 75, p. 307-316.
- Dunn, C.E., 1982, Geology of the Middle Devonian Dawson Bay Formation in the Saskatoon potash mining district, Saskatchewan: *Saskatchewan Energy and Mines Report 194*, 117 p.
- Faure, G., 1977, *Principles of isotope geology*: John Wiley and Sons, New York, 464 p.

- Fuzesy, A., 1982, Potash in Saskatchewan: Saskatchewan Energy and Mines Report 181, 44 p.
- Fuzesy, L.M., 1983, Petrology of the Middle Devonian Prairie Evaporite potash ore in Saskatchewan, in R. Macdonald, T.I.I. Sibbald, D.F. Paterson and P. Gulio, eds., Summary of Investigations 1983, Saskatchewan Geological Survey: Saskatchewan Energy and Mines Miscellaneous Paper 83-4, p. 138-143.
- Gendzwill, D.J., 1978, Winnipegosis mounds and Prairie Formation of Saskatchewan - seismic study, in Economic Geology of the Williston Basin, Montana Geological Society 24th Annual Conference, p. 121-130.
- Hitchon, B., and I. Friedman, 1969, Geochemistry and origin of formation waters in the Western Canada Sedimentary Basin — I: Stable isotopes of hydrogen and oxygen: *Geochimica et Cosmochimica Acta*, v. 33, p. 1321-1349.
- Holter, M.E., 1969, The Middle Devonian Prairie Evaporite of Saskatchewan: Saskatchewan Department of Mineral Resources Report 123, 133 p.
- Parker, J.M., 1967, Salt solution and subsidence structures Wyoming, North Dakota and Montana: American Association of Petroleum Geologists Bulletin, v. 51, no. 10, p. 1929-1947.
- Prugger, F.F., 1979, The flooding of the Cominco potash mine and its rehabilitation, in A.H. Coogan and L. Hauber, eds., Fifth symposium on salt, Northern Ohio Geological Society, v. 1, p. 33.
- Schwartz, F.W., K. Muelenbachs, and D.W. Chorley, 1981, Flow-system controls of the chemical evolution of groundwater: *Journal of Hydrology*, v. 54, p. 225-243.

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EVALUATION AND GEOLOGY OF KAOLINIZED SEDIMENTS, WOOD MOUNTAIN, SASKATCHEWAN

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ABSTRACT

Ekaton Industries Inc. of Calgary, Alberta, has over 100,000 acres of prospecting permits in the Wood Mountain area of southern Saskatchewan. Over 375 million short tons of kaolinized sediments in the Upper Cretaceous Whitemud Formation have been outlined by surface mapping and drilling. Discussions and conclusions on the possible mode of origin of the kaolinized sediments and on their relationship with older and younger formations are based on preliminary data.

The Whitemud sediments are similar to the underlying Upper Eastend sediments except for the degree of alteration to kaolin of their contained feldspars. The sediments, possibly derived from the same source area, were transported over relatively short distances. Exact location of the source area is not specified.

When altered pseudomorphs of feldspar are taken into account, enough feldspar was available to account for post-depositional kaolinization of the Whitemud sediments. If kaolinization had been complete in the source area, feldspar pseudomorphs would probably have been destroyed during transport.

In the kaolinized and unkaolinized sediments, 20 to 25 per cent clay-fill material, most of which appears not to have been derived by in situ alteration, is present. Although difficult to identify in thin section, if this clay-fill material is kaolin, the altered feldspars in the sediments are not the source of the kaolin, which must have been transported and deposited with the Whitemud sediments.

A possible mechanism for folding of the Whitemud and Eastend sediments is subsurface solution of underlying Devonian Prairie Evaporite beds. Crests of collapse structures were eroded prior to the Tertiary Period.

INTRODUCTION

The Whitemud Formation of southern Saskatchewan and southeastern Alberta is a potential source of kaolin. The white outcrops of the Formation, named by Davis (1918), provide excellent stratigraphic markers. The type locality is in the southeastern part of Cypress Hills on the Frenchman River near the Whitemud post office.

In southwestern Saskatchewan, the Whitemud Formation is distributed somewhat erratically with one large area of exposure in the Eastend-Shaunavon area and another at Wood Mountain. Both areas have excellent road and rail systems. The Wood Mountain area lies within 120 km (75 miles) of where the Trans-Canada Highway passes through Moose Jaw, Saskatchewan. The closest supply centre is Assiniboia, about 65 km (40 miles) away by paved road. A spur line of the Canadian Pacific passes through Assiniboia and Wood Mountain (Fig. 1). In the Wood Mountain area, Ekaton Industries Inc. of Calgary has ten prospecting permits covering over 42,000 hectares (100,000 acres) which include a large percentage of known exposures of the Whitemud Formation (Fig. 2).

Selection of the permit areas by Ekaton was based on a search of the literature because considerable work on the clay resources of Saskatchewan has been done by earlier workers

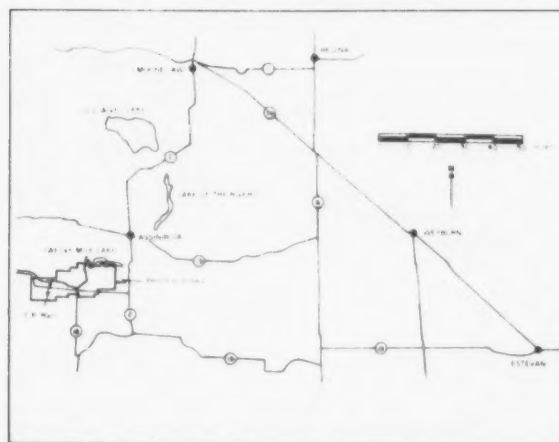


Figure 1. General location map.

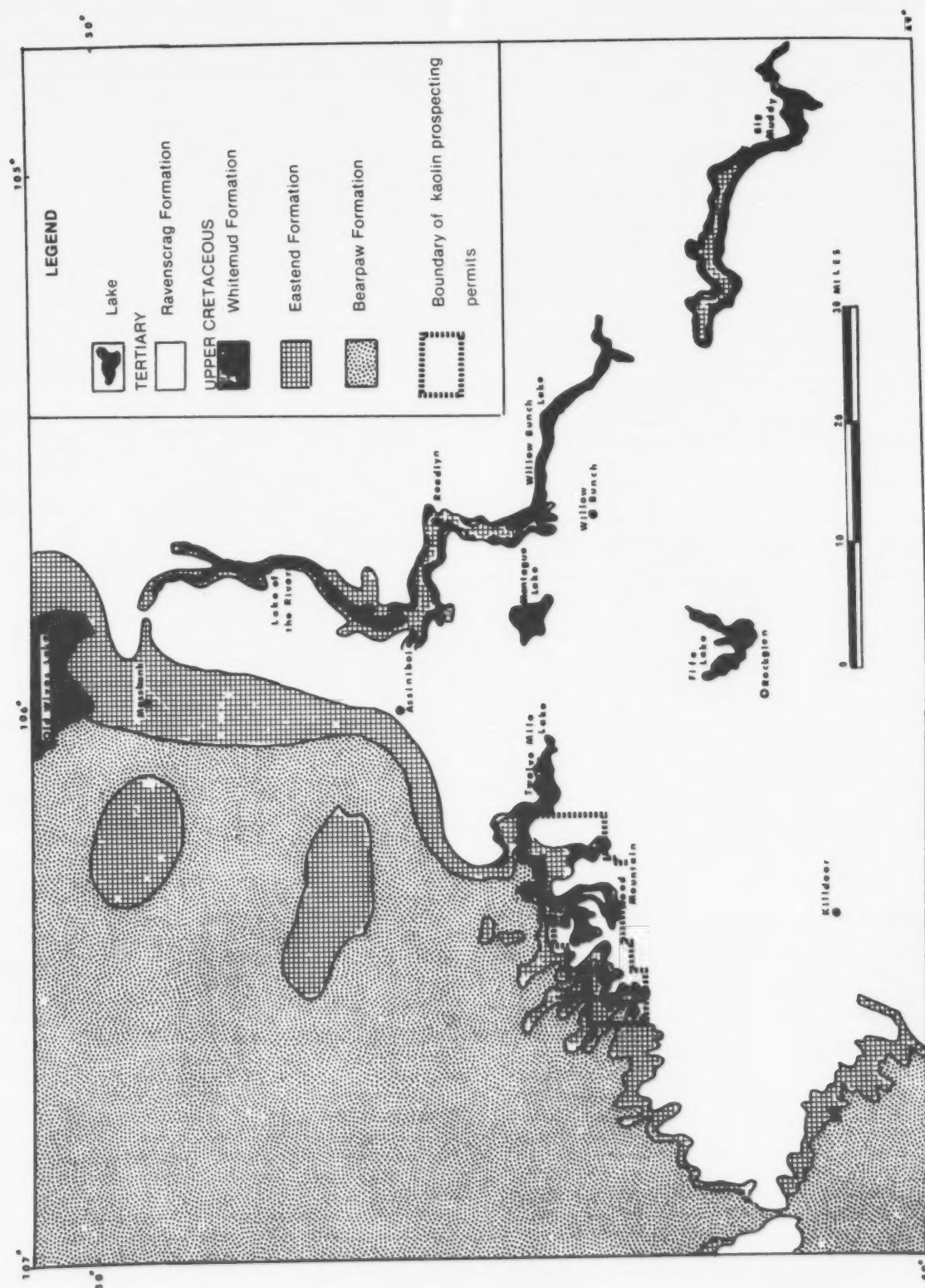


Figure 2. Map showing the general geology of the Wood Mountain region (from Pearson, 1962).

(Ries and Keele, 1913; Davis, 1918; Williams and Dyer, 1930; Fraser et al, 1935; Worcesier, 1950; Pearson, 1962; Guliov, 1984).

From 1948 to 1954, a program of drilling for industrial minerals was completed by the Saskatchewan Department of Mineral Resources. Three drill sites of that program are situated within Ekaton's prospecting permits. On one of these sites, designated as Project 12, a bulk sample was also taken and a pilot-plant study was reported (Spyker et al, 1954). During 1984-85, a bulk sample was taken by Ekaton at the Project 12 site and sent to the Saskatchewan Research Council (SRC) in Saskatoon. The preliminary tests at SRC, with follow-up testing at the Colorado School of Mines Research Institute (CSMRI), indicated that the kaolin could be readily extracted and had properties suitable for the making of mineral fillers. Preliminary market research by Ekaton also indicated that transportation costs from a plant situated in Saskatchewan to other parts of Western Canada and to the United States are competitive with costs for a plant situated in Georgia.

In 1985, a test drilling program of 106 holes totalling 2,900 m (9,500 feet) was completed by Ekaton on the Wood Mountain permits. The drilling was generally on one-mile centres, and designed mainly to outline the extent of the deposit(s). A rotary AV 1000 CRS drill rig was used under contract from SDS Drilling Ltd. of Calgary. Also during 1985, the outcrop areas of Whitemud Formation were mapped and sampled.

GEOLOGY

GEOMORPHOLOGY

Along the southern margin of the permit block is the Wood Mountain Upland, the dividing line between the Old Wives Lake drainage to the north and the Missouri River drainage basin to the south. Topographic relief of the Old Wives Lake Plain is low, becoming gradually more rugged southward into the Wood Mountain Upland. Major steep-sided valleys, 15 to 90 m (50 to 300 feet) deep and up to five kilometres (three miles) wide, occur in the area (Whitaker, 1965). Twelve Mile Lake occupies one such valley, a meltwater channel formed towards the close of the last glaciation. Most bedrock exposures in Ekaton's permit block occur along these steep-sided stream channels.

Cover of glacial drift is thin or absent. The western half of the permit area is covered by hummocky moraines composed mainly of sand with minor amounts of till. The eastern half of the area is a bedrock upland with a thin veneer of glacial drift (Whitaker, 1965) consisting of relatively flat areas separated by deep, steep-sided drainage channels.

REGIONAL GEOLOGICAL SETTING

The Ekaton permits are along the main contact between Tertiary and Upper Cretaceous rocks (Fig. 2, adapted from Pearson, 1962). West of this line, most of the bedrock exposures are of Upper Cretaceous strata. East of the line, the area is underlain mainly by Tertiary rocks although large inliers of Upper Cretaceous rocks are located along Lake of the Rivers, Willow Bunch Lake, and Big Muddy Lake valley. Generally, the strata dip eastward toward the centre of the Williston Basin but local folds cause deviations from the regional trend.

The permits are located a considerable distance south of known salt deposits of the Middle Devonian Prairie Evaporite.

Some salt-free areas were, in the geological past, underlain by the Prairie Evaporite, and salt was removed by subsurface solution. Some portions of the salt may have been removed later in the Tertiary Period, following deposition of the Ravenscrag Formation (Whitaker et al, 1978). In addition to the better known, large collapse structures in the area, such as Hummingbird, evidence from the 1985 drilling program suggests that localized features near Wood Mountain may also be due to post-Whitemud (possibly post-Ravenscrag) salt removal and collapse.

The Bowdoin Dome, which is centred in Montana, extends north into Saskatchewan with its axis approximately 14 km (9 miles) west of Ekaton's permit block.

GEOLOGY OF EKATON'S PERMIT AREA

The main interest is in extensive deposits of kaolinized sediments which have been outlined by outcrop mapping and drilling in the Wood Mountain area. The kaolinized sediments are mainly part of the Whitemud Formation and partly of the Upper Eastend Formation, both high in the Upper Cretaceous Series (Tables 1 and 2).

The sediments of the Whitemud and Eastend Formations are similar in mineralogy and chemistry but differ in the amount of kaolinization. Feldspars (including altered pseudomorphs) are recognizable in both the kaolinized and the relatively unkaolinized sediments of the Whitemud and Eastend Formations. In fact, feldspar pseudomorphs are abundant in even the most kaolinized sediments. The sediments of the Whitemud and the Eastend Formations are possibly derived from the same source area, and most of the kaolinization may have occurred in situ following deposition. The amount and nature of feldspar alteration was a function of the environment of deposition which was variable over short lateral distances and over short time spans. Identification of secondary clay-fill material is necessary to determine if the altered feldspars are the main source of the kaolin.

Local structures within the Whitemud and Eastend Formations, as interpreted from the 1985 mapping and drilling programs, may be related to subsidence of the sediments following the solution of the underlying Devonian Prairie Evaporite. At and adjacent to the crests of some structural highs, the Whitemud Formation was eroded off. A few of the features may be related to Tertiary collapse structures described by Whitaker et al (1978), but new evidence suggests that most of the structural highs were eroded prior to the deposition of the Ravenscrag Formation (Tertiary).

STRATIGRAPHY AND LITHOLOGY

Sections published in the literature are combined with the results of Ekaton's 1985 drilling program to compile Table 2.

Fine to medium sands, silts and clays show cyclic repetition in the Upper Cretaceous and Tertiary strata. The Whitemud Formation, composed of white kaolinized sediments, is the only distinct marker horizon. Some of the colour differences, which cut across formational boundaries, are probably a result of post-depositional processes. In the absence of the white kaolinized marker beds, formation identification from lithology is difficult. For example, the Ravenscrag and Frenchman Formations are almost indistinguishable from the Eastend Formation in drill holes unless the white kaolinized sediments of the Whitemud are present.

Table 1. Cretaceous - Pleistocene stratigraphy in southwestern Saskatchewan.

SYSTEM	SERIES	FORMATION
QUATERNARY TERTIARY	PLEISTOCENE	GLACIAL DRIFT
	PLIOCENE	
	MIOCENE	WOOD MOUNTAIN
	OLIGOCENE	CYPRESS HILL
	EOCENE	SWIFT CURRENT
	PALEOCENE	RAVENSCRAG
CRETACEOUS	UPPER CRETACEOUS	FRENCHMAN
		BATTLE
		WHITEMUD
		EASTEND
		BEARPAW
		BELLY RIVER
		LEA PARK
		UPPER COLORADO
		First White Speckled Shale
		Second White Speckled Shale
		LOWER COLORADO
		Shale
		Fish Scale Zone
		Shale
	LOWER CRETACEOUS	VIKING
		BLAIRMORE

The Ravenscrag Formation is characterized by distinct beds of lignite. Whitaker et al (1978) report that a greenish grey clay or silt band below the lowermost lignite seam forms a distinct lithological marker for the contact between the Ravenscrag and the underlying Frenchman Formation. However, other green sediments lie within the Ravenscrag and Frenchman Formations, and the marker horizon of Whitaker et al (1978) is usable only in conjunction with geophysical logs. In the absence of geophysical logs, the base of the Ravenscrag Formation is considered to be the bottom of the lowest distinct lignite seam.

Older records report that the kaolinized sediments of the Whitemud Formation are overlain by a layer of ball clay, a relationship recognizable in some outcrops. During drilling, however, the ball clay is difficult to distinguish visually from the plastic bentonitic clays of the overlying Frenchman and Ravenscrag Formations. Examination of several outcrops indicates that a distinct unconformity exists on top of the kaolinized sediments so that in places the kaolinized sediments and the ball clay are overlain by the Frenchman, while in others they are directly overlain by the Ravenscrag. In many places, the ball clay is absent and the kaolinized sediments are overlain directly by the Frenchman or Ravenscrag Formations. The upper contact of the Whitemud is generally marked by a downward colour change to white or greyish white. The lithology above this contact is variable, and, in the absence of the kaolinized sediments, difficulty exists in determining if the drill intersections represent the section above or below the Whitemud Formation.

The Whitemud sediments vary laterally and vertically over several metres (a few feet) between the following lithologies:

- 1) kaolinized feldspathic sands and sandstone,
- 2) clayey (kaolinitic) sand and sandstone,
- 3) consolidated sandy clay (kaolin), and
- 4) consolidated clayey (kaolinitic) fine sand and fireclay.

The sediments range in colour from white to yellow to grey and greyish green with gradations between. The dark minerals, identifiable with a hand lens, consist mainly of chert but some carbon grains (coal?) are also generally present. The dark chert and carbon give some of the rocks a salt-and-pepper appearance. The grain size ranges from medium sand to fine sand, silt and clay. Variations in grain size and colour are easily observed in outcrop. With a hand lens, kaolin infillings are distinguishable and distinct lath-shaped clay pseudomorphs after feldspar are recognizable.

The lower contact of the Whitemud Formation with the Eastend Formation is described in the literature as gradational. The contact is generally easy to recognize by colour. It is commonly gradational over five to ten feet (1.5 to 3.0 m) through either grey to yellow feldspathic sandstone, or grey to white clayey sand, siltstone or sandstone. This gradational zone has been termed the Upper Eastend Formation. Part of this Upper Eastend is included in the current reserves of kaolinized sediments; it probably has enough kaolin to be entirely included in the reserves after testing.

The lower contact between the kaolinized sediments (including the partly kaolinized Upper Eastend) and the underlying rocks is marked by a distinct downward colour change to apple green or apple green-grey. The sediments below the kaolinized material are unconsolidated uniform fine sand, partly consolidated fine to medium sand or interbedded silt with clay. The uniform fine sand is designated as the Lower Eastend Formation and the remaining sediments are part of the Upper Transition Zone (see Table 2).

According to Whitaker (1965, p. 33), a Transition Zone separates the Eastend Formation from the underlying Bearpaw. The Upper Transition Zone is coarser grained and, according to Whitaker, should be placed in the Eastend Formation whereas the Lower Transition Zone should be considered as part of the Bearpaw Formation.

The Lower Transition Zone (Table 2) was rarely intersected in the Ekaton drilling program because, even in the absence of kaolinized sediments, the apple-green colour of the Lower Eastend and Upper Transition Zone provided clear indication that the drill was below the potential zone for kaolinized sediments. The bentonitic clays were recognizable from their green colour and vitreous lustre on freshly cut surfaces.

MINERALOGY

Thin sections were prepared of four samples of the Whitemud kaolinized sediments, four samples of the Upper Eastend sediments, three samples of the Lower Eastend — Upper Transition, and one sample of the Lower Transition. The core samples, picked at random from the 1985 drilling program, were provided by Ekaton Industries Inc. The thin sections were examined by Miles Industrial Mineral Research of Colorado.

Quartz grains were identified by undulatory extinction, inclusions and bubble trails, positive optical sign, anisotropy and birefringence. Orthoclase was identified by perthitic

Table 2. Stratigraphy and lithology of part of the Upper Cretaceous and Tertiary sequence in the Wood Mountain region.

TERTIARY	RAVENSCRAG FORMATION		Green-grey, buff feldspathic sandstone, clayey sands, silts and coal seams
	FRENCHMAN FORMATION (?)		Grey-green, purple bentonitic clays, carbon and/or grey-green, yellow sand or sandstone - carbon
			Purple or dark grey ball clay - some sand and silt
	WHITEMUD FORMATION	KAOLINIZED	White to partly yellow, consolidated clayey fine sand to clay (fireclay)
			White and grey, consolidated sandy clay
			Band of iron nodules
			White, grey-green clayey sand and sandstone
			Grey-yellow feldspathic sand or sandstone
	UPPER CRETACEOUS	UPPER PARTLY KAOLINIZED	Grey to white clayey sand, sandstone, silt - carbon. Clay in matrix yellow-orange
		LOWER	Uniform, unconsolidated, fine green-grey sand
	EASTEND FORMATION		Grey to greenish grey, partly consolidated, fine to medium sand or interbedded silt with clay
	UPPER TRANSITION ZONE		Consolidated interbedded grey clays and yellow or grey-white sandstone or grey to apple-green bentonitic clays — variable silt and fine sand
	LOWER TRANSITION ZONE		
	BEARPAW FORMATION		Grey, partly bentonitic shales

texture, clouding (with kaolin?) and minimal twinning. Oligoclase was identified by characteristic albite twinning and negative optical sign. Muscovite was distinguished by parallel extinction and high birefringence. The quartz and muscovite, which tend to be closely associated, possibly represent lithic grains (Byers, 1969).

Pseudomorphs of clay (after feldspar) were recognized by shape and medium birefringence. Kaolinitic clay was distinguished by medium or low birefringence and extremely fine crystal size. Sericite alteration of the grains was recognized by high birefringence and parallel extinction. Miles reported that "clay sediments of low birefringence appear to be deposited between the grains of quartz and feldspar (grains generally touch each other) and do not appear to be altered in situ".

Quartz and feldspar grains have angular edges, suggesting that they have been transported relatively short distances. The muscovite, quartz and feldspar distribution is generally uniform, with larger quartz grains associated with larger muscovite and feldspar grains.

In each thin section, volume estimates were made of mineral constituents based upon grain counts and relative size of the grains (Table 3). A plot (Fig. 3) of the total feldspar content (the sum of the percentage of orthoclase, oligoclase and altered grains) indicates a fairly high percentage of recognizable feldspar grains. If alteration of feldspar (including kaolinization) had occurred in the source areas, many altered feldspar grains would not have survived erosion and transport. On the other hand, the altered feldspar content

of the kaolinized sediment is not much different from that of the partly kaolinized and unkaolinized material, varying between twenty and thirty per cent in all samples except UT-1 (Table 3).

The question arises as to why the feldspar altered to kaolin in the Whitemud but not in the other sediments. Perhaps the level of the water table and climatic conditions during and following deposition favoured alteration of feldspar to kaolin in the Whitemud. These conditions may have varied in a way that accounts for the degree of local kaolinization in the Whitemud and Upper Eastend sediments.

On the other hand, the feldspars may not have been the source of the kaolin, which is, rather, fill material. Miles found difficulty in identifying the clay-fill material but indicated that the clay fill between the quartz and feldspar grains "does not appear to be altered in situ", because the material is uniformly distributed in the interstitial spaces. If the fill material were secondary, and if it were to be identified as predominantly kaolin in the Whitemud sediments, then the kaolin in the Whitemud may be detrital in origin. The same amount of clay fill occurs in the unkaolinized Eastend-Transition sediments (Fig. 4), so the source area of clay fill material was perhaps different in Whitemud time from what it had been earlier.

A plot of the volume percentages of quartz and clay-fill minerals in the sediments of the Whitemud and the underlying Eastend/Transition sediments (Fig. 4) shows that feldspar, quartz and clay-fill contents are similar for most of the sediments except for one of the Upper Transition samples (UT-1). This probably indicates a common source area for the sediments.

Table 3. Volume percentage of mineral components in sediments of different formations (1. Kaolinized Whitemud; 2. Upper Eastend; 3. Lower Eastend; 4. Upper Transition; 5. Lower Transition).

Sample No.	Formation	Quartz	Oligoclase	Orthoclase	Muscovite	Altered grains	Clay fill
2-2*	1	50	-	5	trace	30	10
P12-1	1	50	-	5	trace	25	20
59-14	1	40	trace	10	trace	30	20
FC-1	1	50	-	-	trace	30	20
UE-1*	2	40	trace	5	trace	30	10
UE-2	2	50	trace	-	trace	30	20
UE-3	2	50	-	-	trace	30	20
UE-4	2	50	trace	-	trace	30	20
LE-1	3	45	trace	5	trace	25	25
UT-1	4	25	-	-	trace	-	75
UT-2	4	50	10	-	trace	20	20
LT-1	5	40	-	5	trace	30	25

* Samples contain 5 per cent (2-2) and 15 per cent (UE-1) unidentifiable matter.

STRUCTURE

Moderately thick, dark lines in Figure 5, a structure map of the top of the kaolinized sediments of the Whitemud Formation, represent the present limits of the kaolinized sediments based on outcrop and drill data. Regional dip of the kaolinized sediments, which is generally eastwards, is shallow in the eastern half of the permit block.

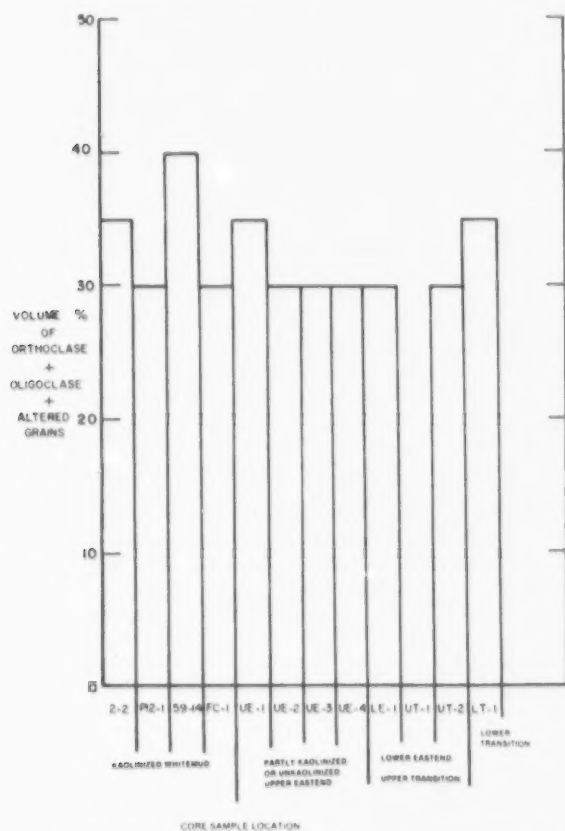


Figure 3. Estimates of feldspar contents in Whitemud sediments, and in the underlying Eastend and Transition sediments.

The kaolinized sediments appear to be folded into four ridges, Project 12 Ridge, Waverly Ridge, Wood Mountain Ridge and Gollier Ridge. Except for last of these, they trend east-northeast.

The projected crests of the Project 12, Waverly and Wood Mountain Ridges lie between the limits of the kaolinized sediments; these crests were eroded off in post-Whitemud, pre-Ravenscrag time. A structure-contour map of the top of the Lower Eastend Formation or Upper Transition Zone (Fig. 6) shows structural highs that coincide fairly closely with the projected ridge crests on the top of the kaolinized sediments (Fig. 5). Crests of Waverly Ridge and Wood Mountain Ridge (Fig. 6) directly overlie a prominent structural high in Figure 5 with a similar coincidence under the Project 12 Ridge. The relationship of the Gollier Ridge in Figure 5 to the structure underneath (Fig. 6) is unclear, possibly because of scanty drill data.

The base of the Tertiary Ravenscrag Formation (Fig. 7), defined as the bottom of the lowest distinct lignite seam, shows a general northeasterly dip and some degree of structural similarity with the top of the Whitemud Formation kaolinized sediments (Fig. 5).

Figure 8, four west-east cross-sections viewed from the south through Ekaton's permit area, shows the Tertiary-Upper Cretaceous structure. The zone between the Ravenscrag and the Whitemud or Lower Eastend is assumed to be the Frenchman Formation. The kaolinized sediments appear to be of fairly uniform thickness wherever they have been encountered, and they may at one time have been fairly continuous. Later, probably before the Tertiary Period, the Upper Cretaceous formations (including the Whitemud) were involved in a major deformation which created several "ridges". The Whitemud sediments at the crest of the ridges were stripped off prior to the deposition of the Ravenscrag. The existing deposits of the Whitemud and Upper Eastend kaolinized sediments are remnants, preserved on the flanks of these ridges. Isopachs of the kaolinized sediments (Fig. 9) indicate that they are thinner towards the projected crests of the ridges, a result of differential erosion between the crests and the more protected flanks of the ridges.

The available data provide no evidence as to whether the Tertiary Ravenscrag sediments were also involved, partly

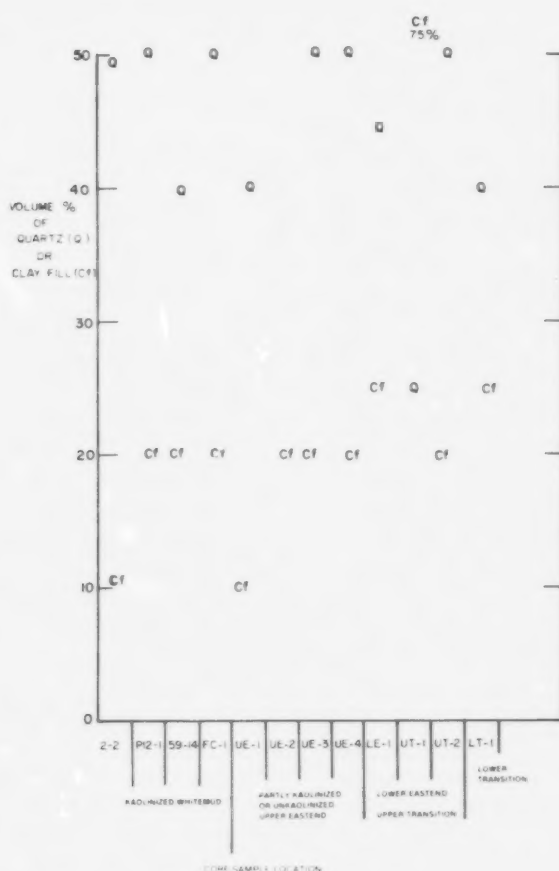


Figure 4. Estimates of quartz (Q) and clay-fill (Cf) contents in Whitemud sediments, and in the underlying Eastend and Transition sediments.

because — during the drilling program — information about the structure of the Ravenscrag was not consistently recorded. The Frenchman Formation appears to wedge out eastwards on the Ekaton permits, and the Ravenscrag directly overlies the Whitemud and Lower Eastend Formations in the south and east (Figs. 7 and 8).

DISCUSSION

GENESIS OF THE KAOLIN

According to Byers (1969), the non-marine sediments of the Whitemud and the Upper Eastend Formations were derived from the same source area. Byers suggested that the source area was in Montana whereas McLearn (Fraser et al, 1935) proposed that it was in the Purcell and Selkirk Mountains, British Columbia.

Drill core and outcrop samples from the Ekaton 1985 drilling suggest that the kaolinized sediments of the Whitemud, the partly kaolinized sediments of the Upper Eastend, and the unkaolinized sediments of the Lower Eastend/Upper Transition are mineralogically similar. The degree of feldspar alteration also seems to be similar, but the alteration products are different.

The angular quartz grains in all the formations suggest relatively short distance of transport from indeterminate source areas. They appear to be sorted with respect to grain size and dark minerals (chert). After initial deposition, the sediments of the Whitemud may have been reworked and redistributed over short distances. The ball clays probably represent reworked material derived from the underlying kaolinized sediments.

McLearn (Fraser et al, 1935) proposed in situ alteration (kaolinization) of these sediments, the degree of kaolinization being a function of climate and water table. He cited the presence of partly altered feldspars in the kaolinized sediments as evidence. Byers rejected the in situ alteration theory, suggesting that the weathered feldspars described by McLearn (Fraser et al, 1935) were actually "light grey to white, metamorphic lithic grains showing no sign of kaolinization and composed mainly of quartz and white mica" (Byers 1969, p. 330), and that the "feldspar grains (which are usually unaltered) are minor and do not exceed 5 per cent in any of the thin sections studied" (Byers, 1969, p. 322).

Based on petrographic work done on twelve samples of kaolinized, partly kaolinized and unkaolinized material, Miles reported that unaltered feldspar forms less than five per cent of the rocks, and that feldspar pseudomorphs (particularly in kaolinized material) increase the total feldspar content to between thirty and forty per cent.

Strong lithological and mineralogical similarities between the kaolinized sediments and the partly kaolinized and unkaolinized sediments of the Eastend are evidence that all sediments are derived from the same source area.

The amount of feldspar alteration in the Whitemud resembles that in the underlying sediments (Fig. 3). However, most of the feldspar in the Whitemud samples studied by Miles is altered to sericite and kaolin, whereas that in the underlying sediments is altered mainly to sericite. Too few samples have been examined to reach any definitive conclusions, and X-ray diffraction data are not available to identify the clay products in the underlying Eastend and Transition sediments.

Significant amounts of feldspar, which ranges from clay and sericite pseudomorphs after feldspar to unaltered grains, suggest that the kaolin in these sediments was derived from the weathering of the feldspars at the site of deposition. If kaolinization took place in the source area, less kaolin would be present in the form of lath-shaped feldspar pseudomorphs, most of which would have been destroyed during transport.

Identification of clay-fill material is important; if the clay fill is mainly kaolin in the Whitemud sediments and sericite or other clay minerals in the underlying sediments, the feldspar pseudomorphs are almost certainly not the main source of kaolin. Rather, the kaolin was, for the most part, formed in the source area and deposited in the sediments during Whitemud time. The source area of the kaolin clay fill may differ from the source area of the Whitemud host sediments.

SIGNIFICANCE OF THE STRUCTURE OF UPPER CRETACEOUS FORMATIONS

Evidence obtained from the drilling program strongly suggests that the Whitemud, Eastend and the Upper Transition Zone were folded in post-Whitemud and (possibly) pre-Ravenscrag time. The most probable cause was collapse due to solution of

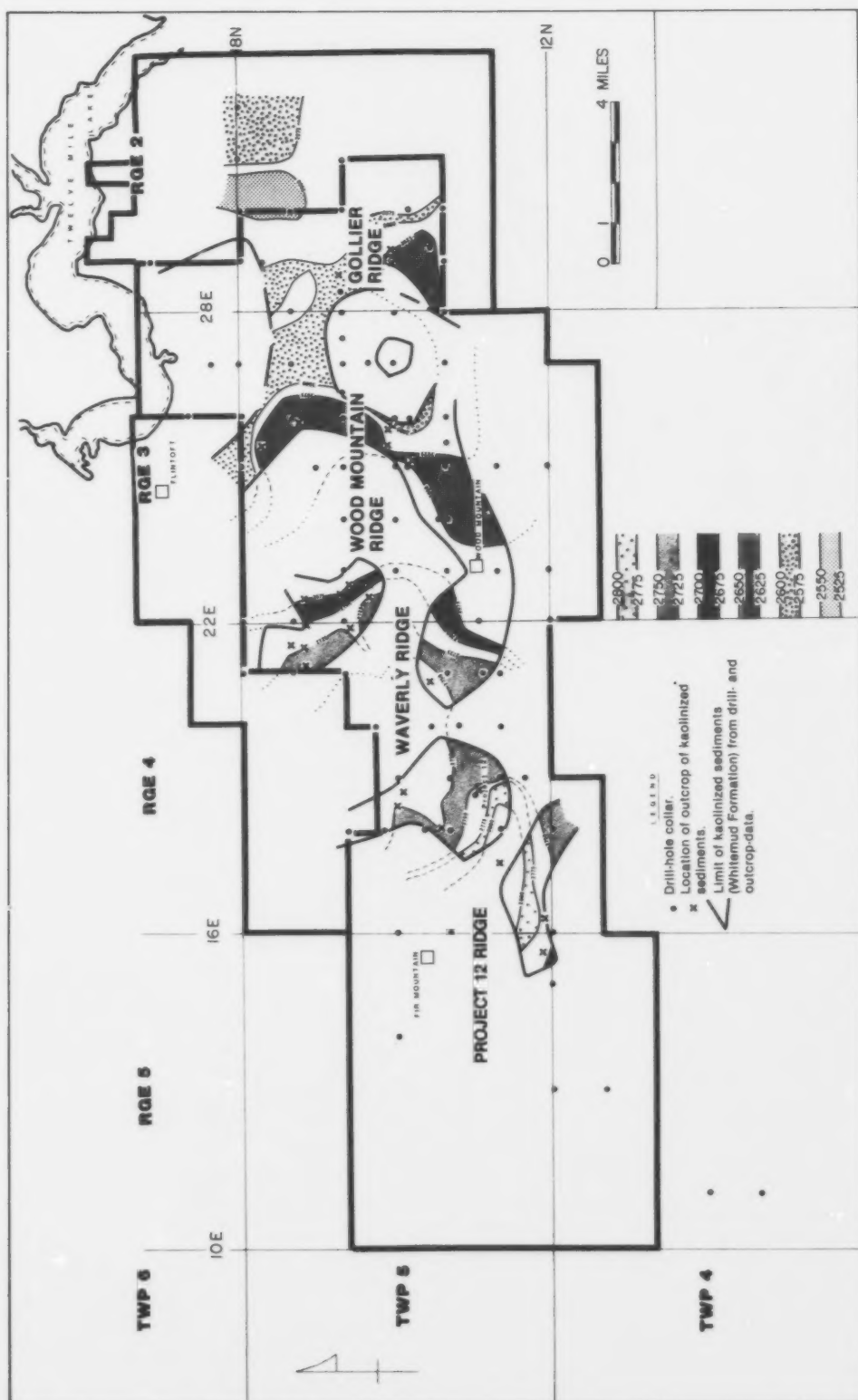


Figure 5. Structure contours of the top of the kaolinized sediments, Whitemud Formation.

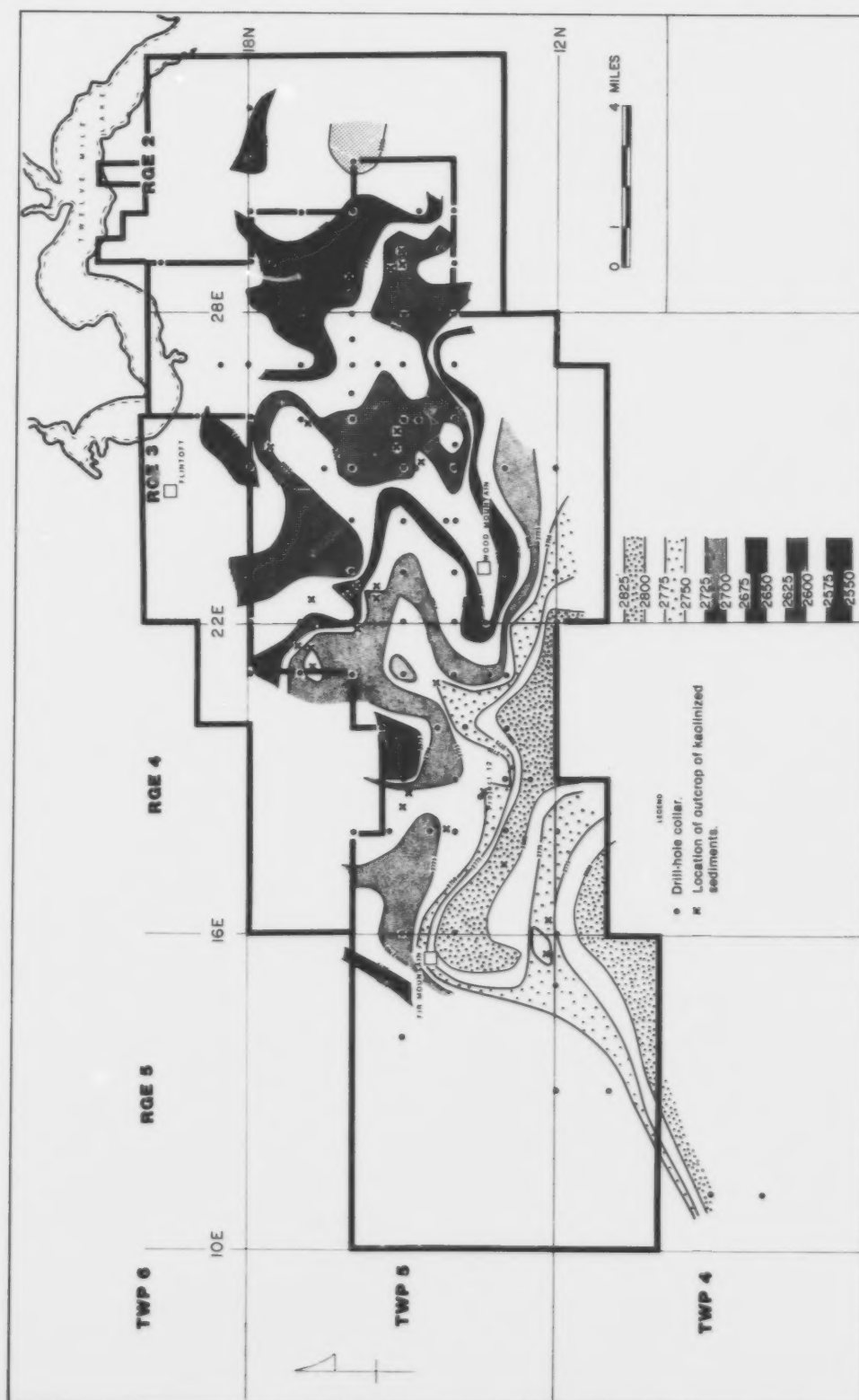


Figure 6. Structure contours of the top of the Lower Eastend Formation or Transition Zone.

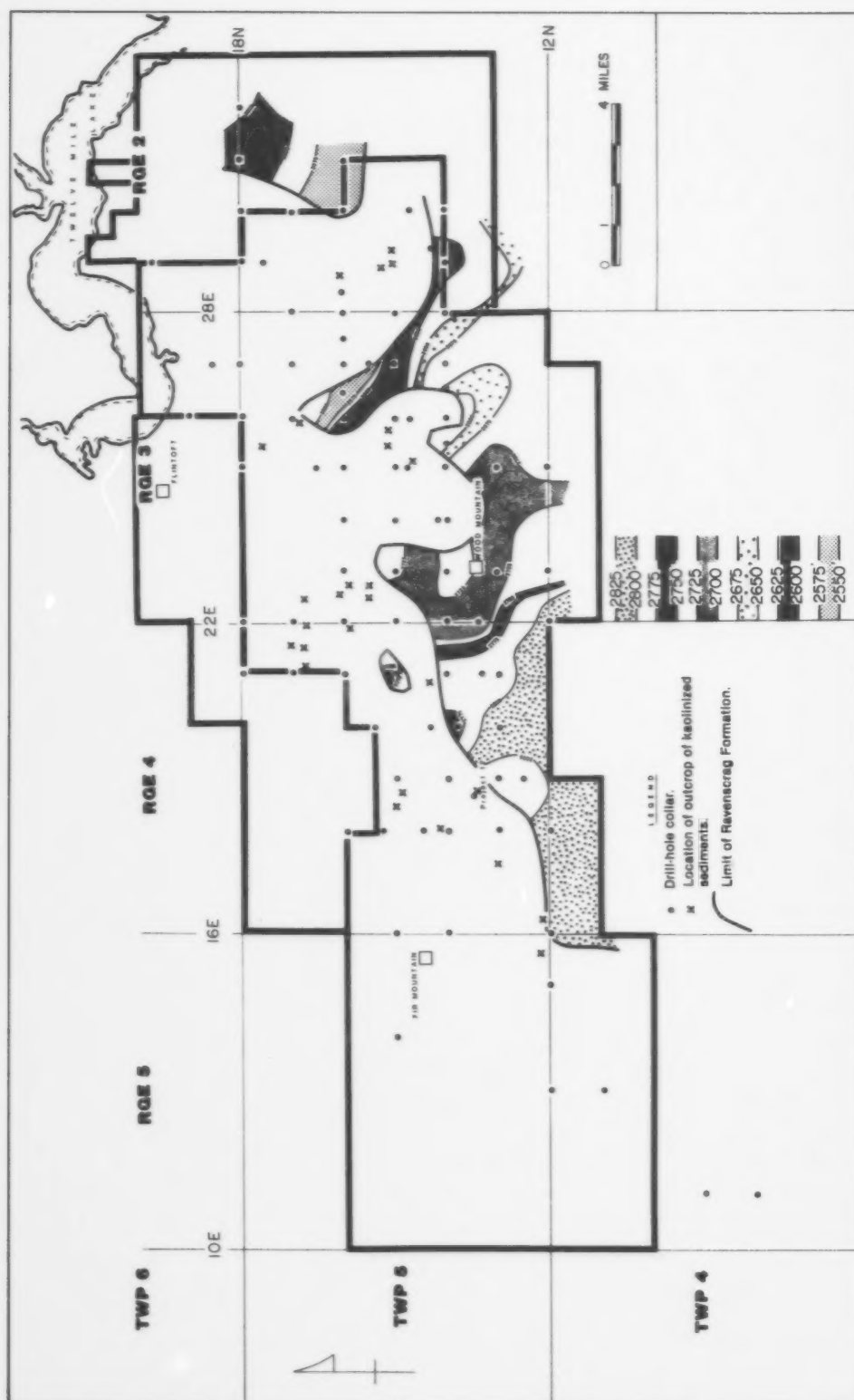


Figure 7. Structure contours of the base* of the Ravenscrag Formation (Tertiary).
* Defined as the base of the lowermost coal seam in the Ravenscrag Formation

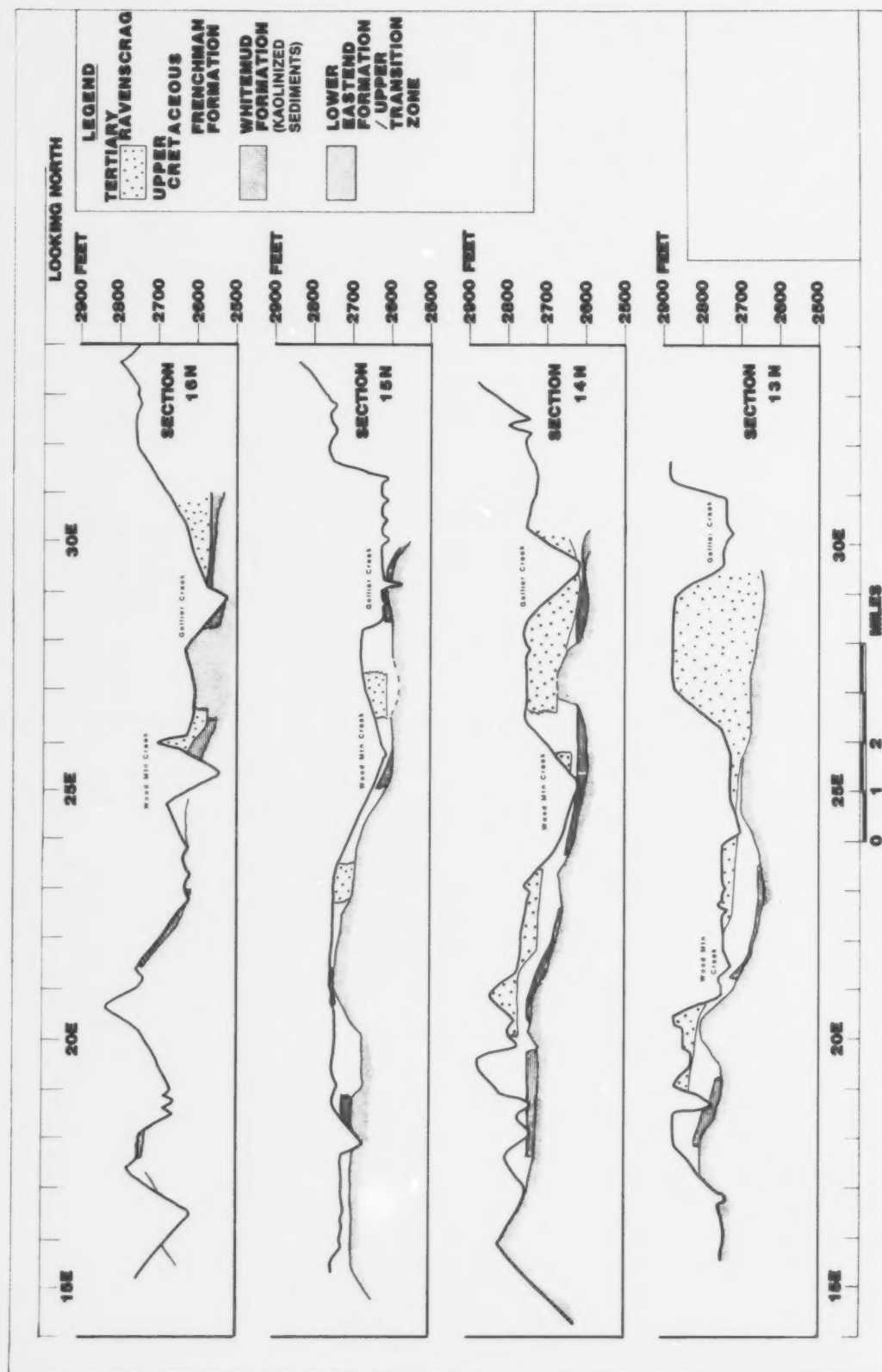


Figure 8. West-east cross-sections viewed from the south; vertical exaggeration approximately 42 times.

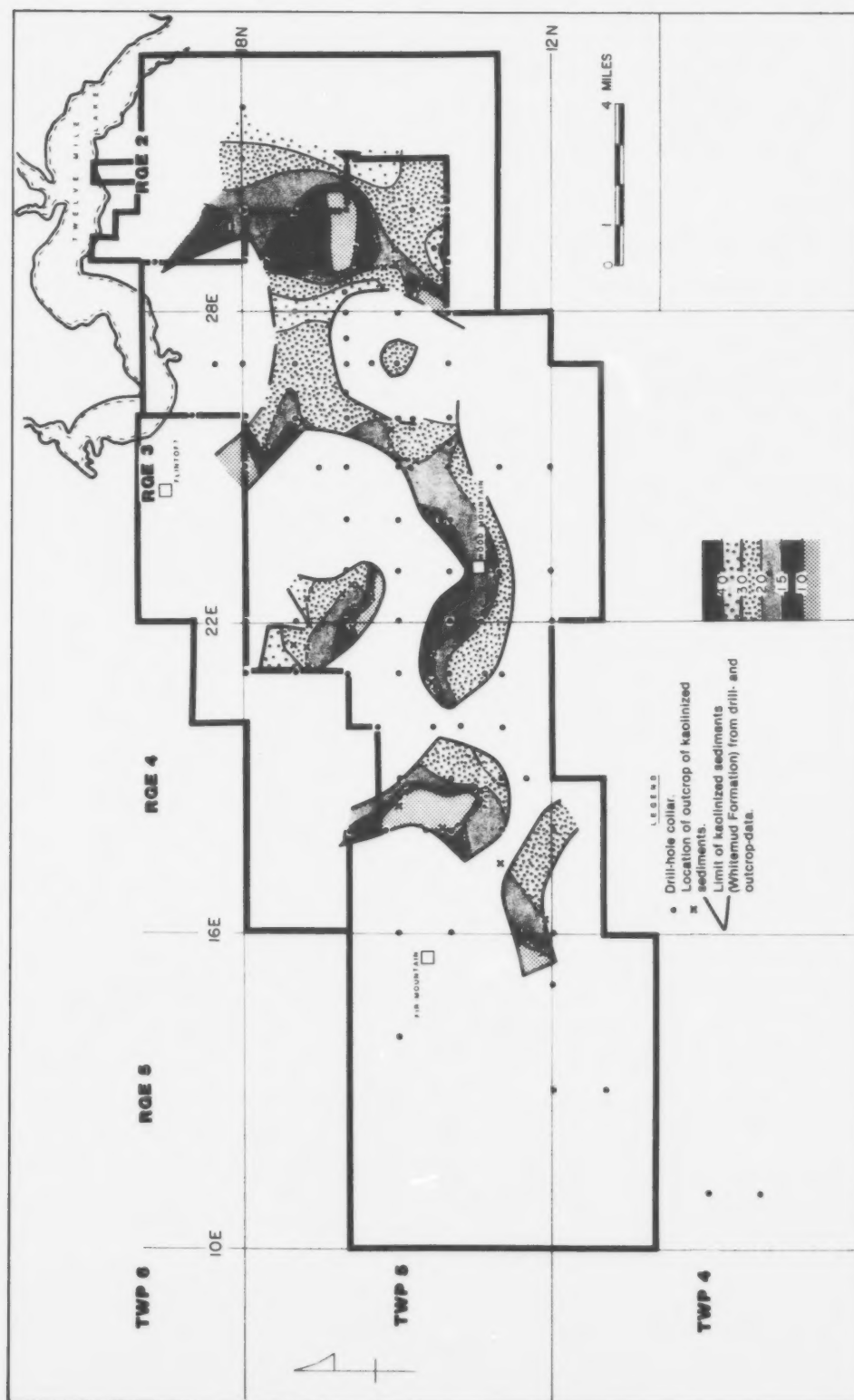


Figure 9. Isopach map of the kaolinized sediments, Whitemud Formation.

the underlying Devonian Prairie Evaporite. Whitaker et al (1978, p. 260) suggest that "small salt remnants were preserved beyond the salt margin of Cretaceous and Tertiary times and were finally dissolved after deposition of the Ravenscrag sediments". The 1985 data does not conclusively show that the Ravenscrag sediments of Ekaton's permit block were also involved in Tertiary collapse structures, but the folding of Upper Cretaceous sediments after deposition of the Whitemud is amply evident (Figs. 5, 6 and 8).

According to Furnival (1946, p. 79) "the Whitemud beds still remaining after the pre-Frenchman erosional period were later removed prior to the deposition of the Cypress Hills beds" (Tertiary). Fraser et al (1935, p. 37, 38) indicate that "the erosional unconformity between the Ravenscrag and Whitemud Formations ... records an interval of erosion at the end of Whitemud time, when in places all of the Whitemud sediments were removed and in some places part or all of the Eastend sediments as well. It is indeed probable that the Whitemud Formation was originally present over nearly all of southernmost Saskatchewan and that the present occurrences are remnants that survived this interval of erosion and the Tertiary and Recent erosion as well".

The interpretation of the 1985 Ekaton data supports the conclusions of Furnival and Fraser et al. Erosion of the Whitemud sediments on the Ekaton permits was probably enhanced by the uplifting of the sediments. The Whitemud sediments found in the 1985 program represent remnants of the sediments preserved on the flanks of folds.

RESERVES OF KAOLINIZED SEDIMENTS

The quantities of in-place material are listed in Table 4. Any part or all of this material may become viable depending on extraction plans and economic assumptions not yet finalized. Reserve estimates took into account the following factors:

- 1) data from the 1985 mapping and drilling program by Ekaton Industries Inc.;
- 2) as far as possible, inclusion of only the sediments between an upper boundary, defined as the contact between ball clays and white kaolinized sediments, and a lower boundary marked by a distinct colour change from white or shades of white to grey or green-grey; in the absence of ball clay and colour variations at the lower contact, other distinguishing criteria have been used (see the section on stratigraphy and lithology, this paper);
- 3) the average thickness of the kaolinized sediments, assumed to be 20 feet (6.1 m);
- 4) the limit of the kaolinized sediments as defined by the 15-foot (4.6 m) isopach; all portions of the deposit fewer than 15 feet (4.6 m) in thickness have been excluded; within the 15-foot (4.6 m) isopach, continuity between outcrops and between drill holes — which are a mile apart on average — has been assumed;
- 5) the bulk density, 1.75, of the kaolinized sediments in situ (an average of measurements completed in a commercial testing facility on outcrop and drill samples submitted by Ekaton), which gives them a tonnage factor of 18.3 cubic feet (0.52 m³) per short ton;

6) isopachs of overburden (Fig. 11), drawn within the boundaries of the 15-foot (4.6 m) isopach of kaolinized sediments;

7) definition of overburden as including Recent sediments and Tertiary and Cretaceous strata above the upper boundary of kaolinized material; this classification facilitates strip-ratio calculations.

Insufficient outcrop and drill samples have been tested for kaolin content; until process testing which is now in progress has been completed, grade boundaries have not been located and the whole deposit has been treated as having a single grade. The blocks within the 25-foot (7.6 m) contour of Figure 10 contain 25-foot-thick (7.6 m) overburden above kaolinized sediments of 20 feet (6.1 m) average thickness; they thus have a strip ratio of approximately 1:1; similarly the 50-, 75- and 100-foot (15.2-, 22.9-, and 30.5-m) contours represent strip ratios of 2:1, 3:1, and 4:1 respectively. Reserve estimates were made by dividing each strip-ratio block into triangular or rectangular portions to help calculate accurately its area, which was multiplied by 20 (average thickness in feet) to obtain its volume and then divided by the tonnage factor to give its tonnage in short tons (Table 4).

Table 4. Summary of geological reserves.

LOCATION	TONS KAOLINIZED SEDIMENTS		
	Strip ratio 1:1	Strip ratio 2:1	Strip ratio 3:1
Waverly	64,480,875		
Wood Mountain	120,218,579	15,846,994	20,765,078
Project 12	19,672,131	24,043,716	18,852,459
Gollier Creek	50,273,224	14,754,098	26,229,508
Subtotal Tons	254,644,809	54,644,808	65,847,045

Total kaolinized sediments with 1:1 plus 2:1 plus 3:1 strip ratios = 375,136,662 short tons

CONCLUSIONS

Data from Ekaton's 1985 program indicate the lithology and mineralogy of the kaolinized sediments of the Whitemud Formation are similar to those of the partly kaolinized and unkaolinized sediments of the underlying Eastend Formation. Evidence for an unconformity below the Whitemud is lacking. Sediments of both formations show evidence that their constituent grains were transported relatively short distances from source areas.

A significantly large percentage of altered and unaltered feldspars was found in every thin section examined; all the feldspar could not have been preserved during transportation if alteration had taken place in the source area. This observation supports McLearn's hypothesis (Fraser et al, 1935) that kaolinization of the Whitemud and Eastend sediments took place after deposition rather than at the source area.

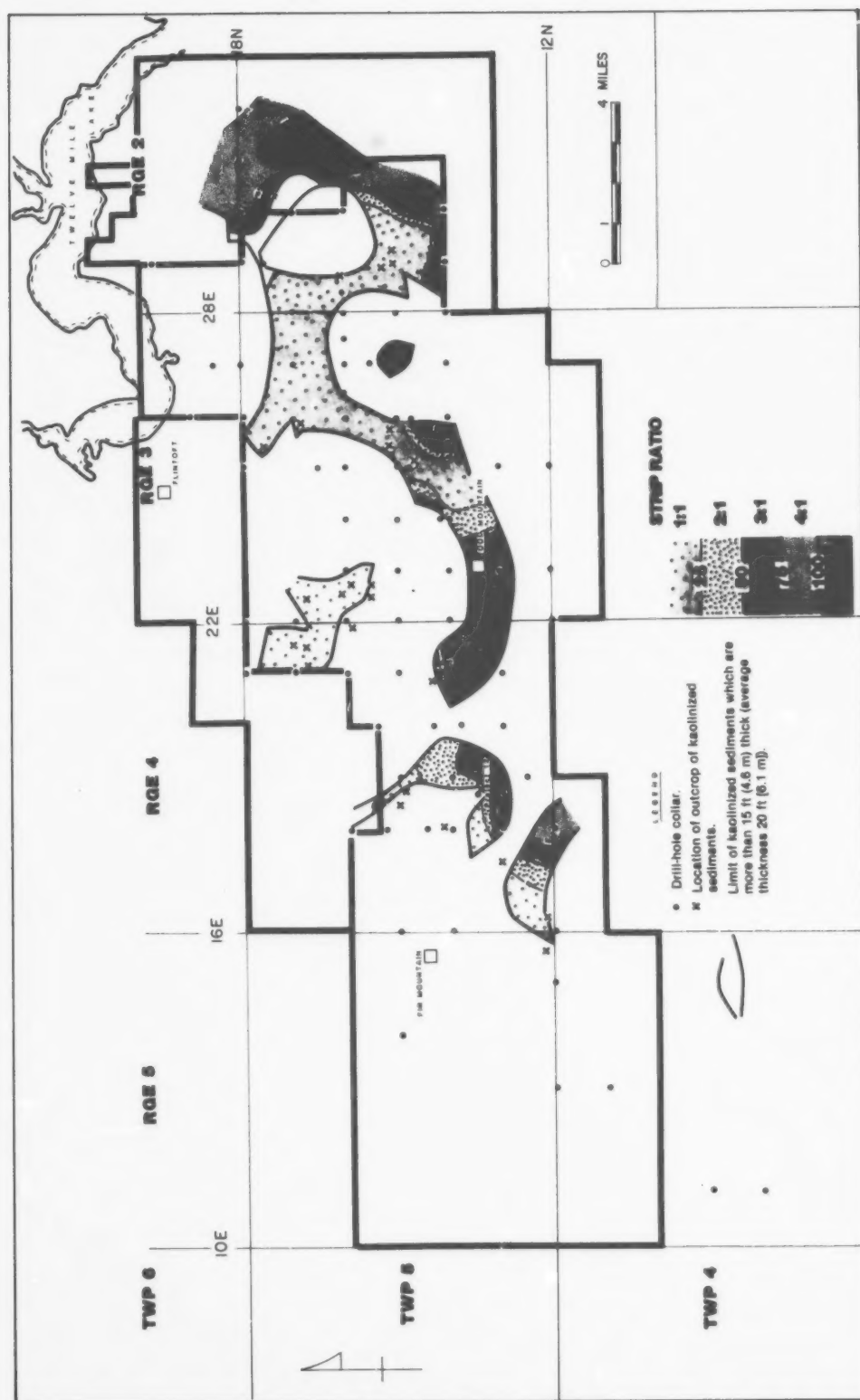


Figure 10. Reserves of kaolinized sediments (Whitemud Formation).

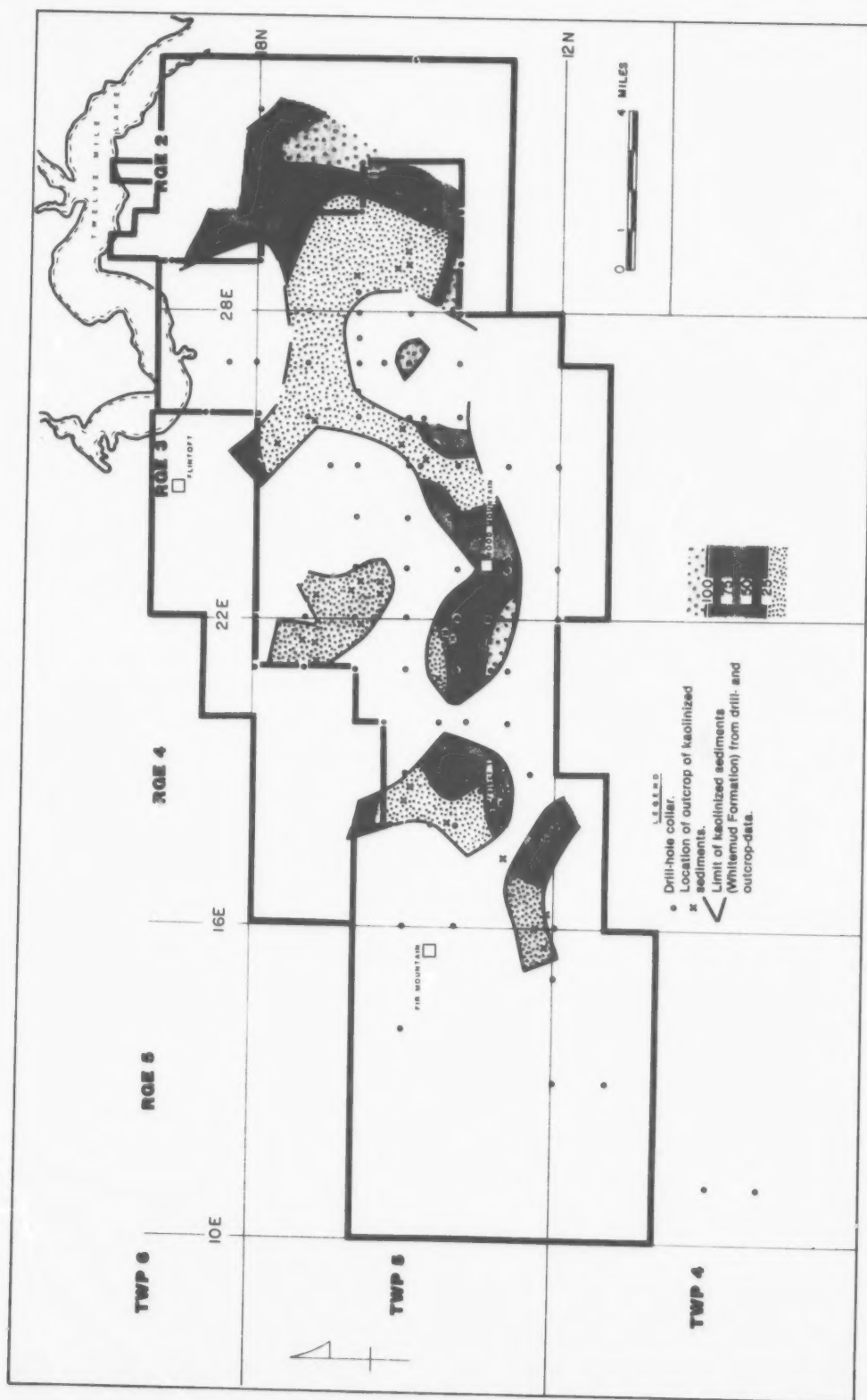


Figure 11. Isopach map of overburden above kaolinized sediments.

However, no data indicate that feldspars were the source of all the kaolin. A large percentage of clay fill occurs in each thin section examined; current evidence suggests that it was not produced by in situ alteration. Although the clay fill in the Whitemud has not been identified in thin section, if it is mostly kaolin, it must have been detrital in origin.

The Whitemud and Eastend sediments at Wood Mountain have almost certainly been affected by post-depositional collapse features. Erosion occurred near crests of ridges, probably accounting for the frequent references in the appropriate geological literature to a post-Whitemud unconformity. The most probable mechanism for these features is collapse due to solution of the underlying Prairie Evaporite.

In situ reserves of 375 million short tons of kaolinized sediments are outlined, assuming geological continuity between widely spaced outcrops and drill intersections. If closer spaced drilling indicates lack of such continuity, either kaolinized sediments have been removed by erosion, or the sediments vary laterally in their degree of kaolinization.

REFERENCES

- Byers, P.N., 1969, Mineralogy and origin of the upper Eastend and Whitemud Formations of south-central and southwestern Saskatchewan and southeastern Alberta: *Canadian Journal of Earth Sciences*, v. 6, p. 317-334.
- Crawford, G.S., and E.Y. Carlson, 1953, Core drilling for industrial minerals in Saskatchewan, 1948-1952: Saskatchewan Department of Mineral Resources Industrial Minerals Report 1.
- Davis, N.B., 1918, Report on the clay resources of southern Saskatchewan: Canada Department of Mines, Mines Branch Publication 468.
- Fraser, F.J., F.H. McLearn, L.S. Russell, P.S. Warren, and R.T.D. Wickenden, 1935, Geology of southern Saskatchewan: Canada Department of Mines, Geological Survey Memoir 176, 137 p., Map 267A and sections.
- Furnival, G.M., 1946, Cypress Lake map-area, Saskatchewan: Geological Survey of Canada Memoir 242.
- Guliov, P., 1984, Summary of industrial minerals in Saskatchewan, in *The geology of industrial minerals in Canada*: Canadian Institute of Mining and Metallurgy Special Volume 29, p. 201-208.
- Pearson, W.J., 1962, Preliminary report on the coal resources in the Wood Mountain-Willow Bunch area of southern Saskatchewan: Saskatchewan Department of Mineral Resources Report.
- Ries, H., and J. Keele, 1913, Clay and shale deposits of the Western Provinces (part 2): Canada Department of Mines, Geological Survey Memoir 25.
- Spyker, J.W., E.Y. Carlson, and W.J. Babey, 1954, Separation of kaolin from kaolinized sand: Saskatchewan Department of Mineral Resources Industrial Minerals Report 2.
- Whitaker, S.H., 1965, Geology of the Wood Mountain area (72G), Saskatchewan: unpublished Ph.D. thesis, University of Illinois, Urbana.
- Whitaker, S.H., J.A. Irvine, and P.L. Broughton, 1978, Coal resources of southern Saskatchewan: a model for evaluation methodology: Geological Survey of Canada Economic Geology Report 30, 156 p.
- Williams, M.Y., and W.S. Dyer, 1930, Geology of southern Alberta and southwestern Saskatchewan: Canada Department of Mines, Geological Survey of Canada Memoir 163.
- Worcester, W.G., 1950, Clay resources of Saskatchewan: Saskatchewan Department of Mineral Resources Technical and Economic Series 2.

RECENT STUDIES ON SASKATCHEWAN CLAYS

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ABSTRACT

The kaolinite-based clay resources of the Whitemud Formation and the Willowbunch Member of the Ravenscrag Formation are briefly described. They were discovered in about 1907. Their industrial utilization reached a maximum in the 1920s, and has since declined, despite considerable drilling out of deposits and development work by the Saskatchewan Department of Mineral Resources in the period 1947-56.

The Whitemud Formation is most thickly developed in a south-central area centring on Wood Mountain, but several outliers are located in the Missouri Coteau country. It consists principally of a mixture of kaolinite and sand (kaolinized sand). In places, stoneware, fire, and ball clays appear to have been deposited in channels in, or to rest upon, the kaolinized sand.

During the last 60 years, numerous papers have described the properties of Saskatchewan high-grade refractory clays, but no commensurate degree of industrial development has followed. Perhaps intensive examination of the kaolinized sands, which occur in much greater quantity than refractory clays, will prove more rewarding.

Spyker et al separated kaolinized sand from the Wood Mountain area and obtained approximately 50 per cent sand (which was of little value due to the proportion of black minerals), 25 per cent of 2 to 12 μm kaolin of reflectance 72, and 25 per cent of less-than-2 μm kaolin of reflectance 69-70. These reflectances are too low even for filling paper. The kaolin could not be bleached by the standard method of acid hydrosulphite; in fact, a point or so of brightness was lost.

At intervals during the past 20 years, the author has tried to bleach this kaolin by standard methods. The only encouraging response has been to cationic flotation with amines whereby material of reflectance up to 79 has been obtained, albeit in only small amounts. Recently, two of the major contaminants have been identified as montmorillonitic material and ilmenite. A method of fractional flocculation with lime to sink the kaolinite and leave the montmorillonitic material up as a sol has been developed with promising results. Reflectances of 75 on the floc and 65 on the sol solids have been attained. High-intensity magnetic separation is an obvious method for separating the ilmenite.

INTRODUCTION

This paper is concerned mainly with identifying the dark contaminants in kaolin extracted from the kaolinized sand member of the Whitemud Formation in southern Saskatchewan. First, however, the geology, distribution, and former industrial importance of this formation, are briefly reviewed.

The Whitemud Formation, a unit of latest Upper Cretaceous age and non-marine origin, has been described at length from a strictly stratigraphic viewpoint by Fraser et al (1935) and by Furnival (1946). Condensing the descriptions of these writers, the Whitemud consists of a sandy clay member which contains much kaolinite at and close to its base, a more-or-less carbonaceous central zone, and a zone enriched in plastic clays — ball, fire, and stoneware — at its top. Post-Whitemud erosion may have removed some or all of these strata from the top down. Another interpretation of the stratigraphy has been given by Lindoe (1965), who recognized cyclic sedimentation

in the Eastend area. Most authors have suggested that the kaolinite was formed in place by the weathering of earlier-deposited feldspathic material, but Byers (1968) proposed that weathering of felsic rocks at source had provided kaolinitic material which was transported to its present position.

The maps of Fraser et al (1935) (Map 267A) and Furnival (1946) (Map 784A) are specific about the location of Whitemud outcrops. The main areas are along Battle and Adams Creeks in the West Block of the Cypress Hills, along the Frenchman River from Ravenscrag east via Eastend to about west longitude 108° 30', along the north side of the Wood Mountain plateau from Fir Mountain to Twelve Mile Lake, and at the south end of Lake of the Rivers. Some widely spaced occurrences are found throughout the Missouri Coteau, but almost all give evidence of glacial thrust-faulting. The most spectacular outcrops in this respect are those at Claybank in the Dirt Hills where the thrust-faulting has been described by Byers (1959).

The plastic-clay-bearing members of the Whitemud Formation attracted industrial attention as soon as railways were built near them. The shipping of stoneware and ball clays from Willows to pottery and sewer-pipe plants in Medicine Hat began some years before 1916, according to Davis (1918). A firebrick plant was established at Claybank in 1916. Underground mining near Willowbunch provided ball clay for shipment to Ohio potteries in the 1920s. Numerous government investigators over the years have described the properties of high quality, light-firing Saskatchewan clays (Ries and Keele, 1912; Davis, 1918; McLearn and McMahon, 1934; Worcester, 1950; and Brady, 1962). During the period 1947-56, the Saskatchewan Department of Mineral Resources drilled out considerable quantities of these high-grade plastic clays and extensively tested bulk samples (Crawford and Carlson, 1953; Carlson and Babey, 1955).

Despite this government-sponsored test work, less clay is now being mined in Saskatchewan than in the past. Vitrified clay sewer pipe remained popular, even after the development of cast-iron and asbestos-cement pipe, but has been unable to compete with plastic pipe. The mass market for medium-heat-duty firebrick disappeared with the introduction of the diesel-electric railway locomotive. Stoneware crocks and jugs have been replaced by lighter, plastic substitutes. Even building brick is being gradually superseded by cheaper concrete imitations. The market for vitrified floor tile (quarry tile) will doubtless continue for as long as shopping malls proliferate, but even the stoneware clays of the Whitemud do not fire to the 0 to 1 per cent absorption (i.e. zero porosity) at cone 5 (1180°C) or lower required for this product.

The bleak future for the industrial utilization of the plastic members of the Whitemud has for some years offered the author and other investigators little incentive to study the resource.

KAOLIN FROM THE KAOLINIZED SAND MEMBER

An alternative question then arises as to what can be done with the kaolinized sand member which constitutes the vast bulk of the Whitemud Formation (a situation which is not apparent from published material). Whitemud outcrops in the Wood Mountain and Willows districts have an average thickness of 6 to 12 m (20 to 40 ft). At least half of them consist only of the kaolinized sand member. The upper plastic zone reaches a maximum thickness of 4.6 m (15 ft), but is more generally about 1.5 m (5 ft) thick. Published accounts of Whitemud occurrences and clay resources (Crawford and Carlson, 1953), are atypical because early clay seekers, in their preliminary field surveys, ignored those with thin or no plastic member.

Spyker et al (1954) separated by relatively simple hydro-classification and settling methods a sample of kaolinized sand from Wood Mountain into a sand fraction, a coarse or ceramic kaolin nominally 12 to 2 μ m e.s.d.,* and a fine kaolin nominally less-than-2 μ m e.s.d. The exact source of the sand was Project 12 of Crawford and Carlson (1953), beds 12-S-4 and 12-S-5, from Sec. 9 Twp. 5 Rge. 5W3. Table 1, mostly after Spyker et al (1954), lists selected properties of the products.

Table 1. Properties of three fractions of Wood Mountain kaolinized sand, Sec. 9 Twp. 5 Rge. 5W3 (mostly after Spyker et al, 1954).

	Sand	Coarse kaolin	Fine kaolin
Yield (per cent)	53.4	21.0	25.6
Chemical Composition (per cent)			
SiO ₂	85.6	53.58	46.58
Al ₂ O ₃	5.9	31.50	36.60
Fe ₂ O ₃	0.65	0.63	1.41
TiO ₂	0.4	0.78	0.23
CaO	0.57	0.25	0.58
MgO	0.23	1.00	0.91
K ₂ O	0.6	1.07	0.86
Na ₂ O	2.6	1.03	0.56
L.O.I.*	2.5	10.71	12.73
Total	99.05	100.55	100.46
Diameter, 50 percentile	100 μ m	5.9 μ m	0.9 μ m
Trigreen Reflectance	n.a.	71.3-72.5	69.5-70.2
Pyrometric Cone Equivalent	n.a.	32	32½

The following observations are evident:

- 1) the sand fraction is too impure chemically, as well as too fine, for glass making,
- 2) nothing seems to be wrong with the coarse kaolin as a possible component of ceramic bodies of the whiteware kind, and
- 3) the fine kaolin is far too dark for use as a paper-filler, let alone a paper-coater, clay. Patterson and Murray (1975) give as minimum reflectance values 80 for filler and 85 for coater clay.

Spyker et al (1954) noted the poor colour of the fine kaolin and reported that standard methods of bleaching, such as treatment with zinc and sulphur dioxide, failed to improve it. They advised that further study be given to the nature of the colouring impurity and possible methods of removal.

The present author, wondering why earlier workers had concentrated on testing kaolinized sand from Wood Mountain, studied the kaolin fraction of kaolinized sands from other sources with the aim of obtaining better yields or colour. Table 2 shows the results of these investigations. The sample locations are indicated by the N.T.S. system (quarter- or half-section, section, township, range and meridian).

Each sample was separated by allowing a dilute deflocculated dispersion of the sand in a cylinder of known height to settle for a time given by Stokes' equation, pouring off the suspended matter, repulping the sand and repeating the process until the supernatant remained clear. A fraction of each separated sample was oxidized by heating it with six per cent NaOCl at 90°C for three hours. Other fractions were reduced with Na₂S₂O₄ plus KHC₄H₄O₆ at pH 3.4.

* e.s.d.: equivalent spherical diameter.

* L.O.I.: loss-on-ignition.

Table 2. Yields and brightnesses of less-than-12 μm fraction of other kaolinized sands.

Sample	Location	Less-than-12 μm fraction (per cent)	Reflectance	Reflectance oxidized	Reflectance reduced	Reflectance both oxidized and reduced
5701 Aquadell	SE $\frac{1}{4}$ -16-20-6W3	40.7	50.8	67.7	67.5	71.5
7511 Boundary Plateau	N $\frac{1}{2}$ -14-1-23W3	33.9	53.5	67.1	64	71.5
7509 Old Medalta Eastend	NW $\frac{1}{4}$ -5-7-21W3	47.9	46.5	59.5	n.d.	68.0
7505 P29 Eastend	SE $\frac{1}{4}$ -6-7-21W3	48.8	49.3	56.8	58	69.5
8001 Cactus Hills	NW $\frac{1}{4}$ -19-13-26W2	55.3	50.6	65	n.d.	64.4
7-S-3 Highway Eastend	S $\frac{1}{2}$ -13-6-22W3	55.4	53.6	63.3	n.d.	n.d.

The yields were the same or less than the Wood Mountain material. The raw reflectance was consistently lower, probably due to lignitic matter, which was removed by oxidation. Acid reduction removed iron-oxide films from the Eastend clay. Maximum reflectances of 71.5 were obtained. The earlier workers had evidently chosen as good a deposit to study as any in the province.

For the less-than-2 μm fine kaolin from Wood Mountain as reported by Spyker et al (1954), reduction with hydrosulphite at pH 3 to 3.5 — a standard method for bleaching out iron — yielded a product of reflectance 67 to 68, a point or so less than untreated kaolin. Oxidation by lengthy treatment with cold H_2O_2 or with warm hypochlorite produced material of reflectance 70.5 to 71, a point or so higher than unoxidized kaolin. These results have been obtained repeatedly. The kaolin should not be left in alkaline hypochlorite more than a day at 90°C and 0.5 N alkali as it begins to change into hydroxysodalite. Material wholly converted to hydroxysodalite has a reflectance of 82. This suggests that at least some of the colourant is a clay mineral.

X-ray diffraction runs of Wood Mountain kaolin show kaolinite of the b-axis disordered type (ASTM P.D.F. card 6-221), quartz, a few of the stronger lines of feldspar, and at least the 10 angstrom peak of mica. Glycolation reveals the absence of montmorillonite. If a discolourant is present in amounts of only a few per cent, the brightness of a sample might be greatly reduced, but recognizable peaks need not appear on a diffractogram.

IDENTIFICATION OF THE CONTAMINANTS

A deflocculated dispersion of 50 g Wood Mountain kaolin in three litres water of pH 8, dispersed with 0.2 per cent $\text{Na}_2\text{P}_2\text{O}_7$, was inadvertently left to evaporate to dryness over a three-month period. The dry cake had an olive-green upper skin, a bright white main mass, and black streaks on the bottom at the outer margin in the region of curvature of the basin's surface.

Samples of these components were separated by hand.

An X-ray diffractogram of the olive-green skin showed major kaolinite, minor quartz, and minor montmorillonite

expanding from 10.3 and 14.5 angstroms in the dry state to 18.8 angstroms on glycolation. After glycolation a trace of the 10 angstrom peak was left but none of the 14 angstrom peak. Hence chlorite was absent, but a little micaceous matter may have been present.

The green skin gave a trigreen reflectance of 27. Calculation from the initial depth of slurry in the basin and the time available for settling put its e.s.d. in the range 0.1 μm or less.

The main mass of whiter material gave a trigreen reflectance of 76 to 76.5. Commercial NaClO solution at 90°C took its reflectance up to 78. Reduction with Zn and HCl lowered its reflectance to 66.2, but hypochlorite treatment returned this to 77.5.

The black streaks on the bottom gave a diffractogram consisting of kaolinite and quartz with minor mica and a trace of feldspar similar to other Wood Mountain kaolin samples. The black minerals were too sparse to permit identification. To enrich the dark contaminants, advantage was taken of observations over the years that the bed settling onto a curved or slanting surface from a deflocculated kaolin dispersion always had a black margin, albeit too thin and narrow to separate and examine. A deflocculated kaolin dispersion was confined in a glass tube 1.2 m long x 5 cm (internal diameter) stoppered at both ends and held at an angle of 40° to the horizontal. In a few minutes, a bed formed and continued to extend as long as sedimentation took place. The bed contained a ventral black line which bifurcated towards its lower end (Fig. 1). The upper end of this line extended upward as long as the bed was deposited, showing that the black material exists in all size classes of the kaolin.



Figure 1. Bed seen from below.

A tube one metre long produced a bed with a black strip that permitted enough black material to be collected in pure enough form to report on an X-ray diffractogram. Two such diffractograms gave major ilmenite and minor anatase and rutile, as well as the usual kaolinite, quartz, and trace of mica.

The principal dark contaminants in Saskatchewan kaolin are thus:

- 1) fine montmorillonitic matter (less than $0.1 \mu\text{m}$), and
- 2) ilmenite and titanium oxides.

ATTEMPTS AT REMOVAL OF THE DARK IMPURITIES

Ilmenite should, logically, be removable by high-intensity, wet magnetic-separation.

Flotation separation of ilmenite and similar titanium oxides from kaolin has been described many times (e.g. Mallory, 1974; Cundy, 1968), but so far this laboratory has had little success in collecting these titanium minerals, possibly because all the particles are in the mineral-dressers' "slime range". Unorthodox methods such as the carrier flotation of Greene and Associates (1961), the column flotation described by Dobby and Finch (1986), or the autogenous generation of bubbles by boiling or vacuum, might produce successful separations.

Selective flocculation of kaolin from finer montmorillonitic matter by cationic acrylamide polymers is another separation technique which has been tried at this laboratory without success, perhaps because effort was not persistent enough or because the polymers used were unsuitable. Kaolin floc produced by cationic acrylamide polymers is gummy, and the polymers have to be removed (by oxidation for example) before the kaolin is saleable. Additional costs are thus involved. Selective flocculation should precipitate undesired components, but when the unwanted clay is much finer than the valuable clay and both are chemically similar, this result is virtually impossible to achieve.

Some promising outcomes were obtained by partial flocculation of a kaolin pulp with lime, $\text{Ca}(\text{OH})_2$. A 50 g per litre dispersion of less-than- $12 \mu\text{m}$ kaolin was extracted directly by sedimentation from kaolinized sand with the aid of 0.25 per cent $\text{Na}_2\text{P}_2\text{O}_7$ placed on the sand. To this dispersion in a 500 ml graduated cylinder, 6.2 g $\text{Ca}(\text{OH})_2$ per kilogram kaolin were added (i.e. 150 mg lime in this case), shaken, stirred, and left to stand. After 30 to 60 minutes, the mixture separated into a yellow sol and white floc. In one example, 175 ml of floc and 365 ml of sol were produced, and these contained 21.1 g and 3.0 g solids respectively, having trigreen reflectances of 76 and 71. A problem exists in that, if the floc makes up one-third of the total volume of material produced, it is presumably permeated by mother liquor containing colloidal bentonitic fines, so only two-thirds of the fines have been eliminated. To study this problem further, enough pH 9.5 limewater was added to floc from a like test to make up 500 ml of mixture, which was allowed to settle overnight. More yellowish sol and floc were generated. The results are shown in Table 3.

Table 3. Two-stage lime flocculation.

Property measured	First sol	Second sol	Final floc
Volume	398 ml	385 ml	115 ml
Weight of solids therein	0.7 g	1.7 g	20.4 g
Trigreen Reflectance of solids	65.8	72.4	74.2

The solid obtained from the final floc has a reflectance of 74 to 76, indicating that it still contains ilmenite. It would be considerably brighter if the titanium compounds were to be extracted. The lime-feed concentration is critical: at 4 g/kg the slurry stays dispersed whereas at 8 g/kg all solids flocculate together. These figures would presumably be different for different slurry-solids contents or initial deflocculant dosages. A less-than- $2 \mu\text{m}$ kaolin slurry can also be partially purified by flocculation with lime, but separation is not so clear cut and losses to the sol phase are higher.

CONCLUSIONS

Although no final solutions to the economic problem of making a marketable kaolin from Saskatchewan's Whitemud Formation have been suggested in this paper, two main discolourants have been identified. This advance lends direction to the planning of future clay-production research and feasibility studies.

REFERENCES

- Brady, J.G., 1962, The effect of the mineralogical composition of Whitemud Formation clays on their utilization: Mines Branch Research Report R99, Department of Mines and Technical Surveys, Ottawa.
- Byers, A.R., 1959, Deformation of the Whitemud and Eastend Formations near Claybank, Saskatchewan: Transactions of the Royal Society of Canada, v. 53, series 3, section 4, p. 1-11.
- Byers, P.R., 1968, Mineralogy and origin of the Eastend and Whitemud Formations of south-central and southwestern Saskatchewan and southeastern Alberta (abstract): Bulletin of Canadian Petroleum Geology, v.16, p. 203-204.
- Carlson, E.Y., and W.J. Babey, 1955, Core drilling for industrial minerals in Saskatchewan, 1953-1954: Industrial Minerals Research Branch Report of Investigations No. 6, Saskatchewan Department of Mineral Resources, Regina.
- Crawford, G.S., and E.Y. Carlson, 1953, Core drilling for industrial minerals in Saskatchewan, 1948-1952: Industrial Minerals Research Branch Report of Investigations No. 1, Saskatchewan Department of Mineral Resources, Regina.
- Cundy, E.K., 1968, Bleaching kaolin by froth flotation beneficiation for separation of titania impurities therefrom: Great Britain Patent No. 1,108,585.
- Davis, N.B., 1918, Report on the clay resources of southern Saskatchewan: Canada Department of Mines, Mines Branch Report No. 468, Ottawa.
- Dobby, G.S., and J.A. Finch, 1986, Flotation column scale-up and modelling: Canadian Institute of Mining and Metallurgy Bulletin, v. 79 (889), p. 89-96.
- Fraser, F.J., F. H. McLearn, L.S. Russell, P.S. Warren, and R.T.D. Wickenden, 1935, Geology of southern Saskatchewan: Geological Survey of Canada Memoir 176, Ottawa.

- Furnival, G.M., 1946, Cypress Lake map-area: Geological Survey of Canada Memoir 242, Ottawa.
- Greene, E.W., J.B. Duke, and J.L. Hunter, 1961, U.S. Patent No. 2,990,958.
- Lindoe, L., 1965, Ceramic clays of the Cypress Hills, in R.L. Zell, ed., Cypress Hills Plateau, Alberta and Saskatchewan, Guidebook to 15th Annual Field Conference, part I: Alberta Society of Petroleum Geologists, Calgary, p. 210-225.
- Mallory, M.B., 1974, U.S. Patent No. 3,827,556.
- McLearn, F. H., and J.F. McMahon, 1934, Buff and white-burning clays of southern Saskatchewan: Geological Survey of Canada Summary Report for 1933, Part B, p. 32-157.
- Patterson, S. H., and H.H. Murray, 1975, Clays, in *Industrial Minerals and Rocks*, fourth edition: American Institute of Mining and Metallurgical Engineers, New York, p. 519-585.
- Ries, H., and J. Keele, 1912, Preliminary report on the clays and shales of the western provinces: Geological Survey of Canada Memoir 24-E.
- Spyker, J.W., E.Y. Carlson, and W.J. Babey, 1954, Separation of kaolin from kaolinized sand: Industrial Minerals Research Branch Report of Investigations No. 2, Saskatchewan Department of Mineral Resources, Regina.
- Worcester, W.G., 1950, Clay resources of Saskatchewan: Saskatchewan Department of Natural Resources Technical and Economic Series Report No. 2, Regina.

PETROGRAPHIC CHARACTERISTICS OF COALS FROM THE RAVENSCRAG FORMATION, SOUTHERN SASKATCHEWAN: IMPLICATIONS FOR COAL UTILIZATION

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ABSTRACT

Petrographic characteristics of coal samples from the Hart and Souris seams, Ravenscrag Formation (Paleocene) reveal several lithotypes. The lithotypes identified in the Hart seam (Willow Bunch coalfield) are:

- 1) xylitic coal,
- 2) attrital coal,
- 3) xylitic/attrital coal (numerous varieties), and
- 4) impure coal.

Inclusions of fusitic coal are present in the attrital coal components.

Correlation between lithotype and maceral composition is good. More than 90 per cent of the xylitic coal consists of reactive humotelinite and humocollinite macerals. Inertinites account for over 40 per cent of the attrital coal. In the xylitic/attrital coal, the inertinite content increases as the proportion of the attrital component increases; humodetrinite increases likewise.

The Souris seam (Estevan coalfield) contains more liptinite and less inertinite, on average, than the Hart seam coal. The rank of the Souris seam (0.34 to 0.36 per cent R_m), determined on the basis of huminite reflectance, is greater than the Hart seam (0.18 to 0.22 per cent R_m). The higher rank and reactive maceral composition of the Souris seam make it a suitable feedstock for coal conversion. Good coal conversion feedstocks can also be obtained from the Hart seam by selecting xylitic/attrital coal dominated by xylitic components and liptinite-rich horizons.

INTRODUCTION

Whitaker et al (1978) conducted an extensive resource evaluation together with stratigraphic studies of the coals in the Paleocene Ravenscrag Formation of southern Saskatchewan (Fig.1). Some of the coal zones described have been studied using petrographic methods. Cameron (1978b) reported on the maceral compositions of numerous coal seams in the Estevan coalfield. Hagemann (1981) described coal from the Hart seam (Willow Bunch coalfield) and the Estevan seam (Estevan coalfield) in terms of coal lithotypes used to describe European brown coals. Dobell et al (1984) examined three samples from the Hart seam and one sample from the Estevan seam.

Studies of the petrographic characteristics (lithotype, microlithotype, macerals and reflectance) of coal samples from the Hart and Souris zones, currently being conducted at the Energy Research Unit of the University of Regina, have these objectives:

- 1) to investigate vertical and lateral variations in coal quality based on the petrographic characteristics of

coal samples obtained from cores and reverse circulation drill samples, and

- 2) to examine the relationship between the macroscopic character of the coal (lithotype) and the microscopic character (macerals, microlithotype composition) with a view to predicting coal quality.

The microscopic (maceral) composition of a coal ultimately controls the reactivity. If the microscopic and macroscopic characters are correlative, then the reactivity of the coal could be predicted reasonably well on the basis of lithotype identification. The types of coal best suited for combustion, liquefaction or briquetting could conceivably be identified at the minesite by visual inspection. Some preliminary results of this study are reported herewith.

Lithotype analyses were carried out on two cores (3316C and 3166C), both approximately 4.6 m thick, from the Hart seam in the Willow Bunch area. The two cores were taken from wells which are 4.8 km apart. A new lithotype classification is proposed. Fifteen samples, representing selected lithotypes, were quantitatively analysed by optical microscopy to determine maceral composition. In addition, maceral analyses

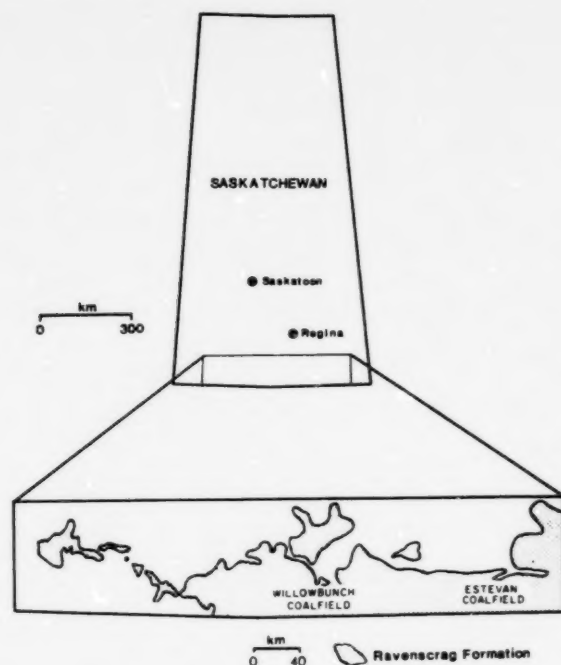


Figure 1. Index map of Saskatchewan showing location of Willow Bunch and Estevan coalfields (modified from Energy, Mines and Resources Canada, 1982).

were carried out on nine coal samples obtained by reverse circulation drilling from four boreholes penetrating the Souris seam (Estevan area). Each of the nine samples represents a vertical interval of coal approximately 0.6 m thick. Reflectance data were obtained for the principal huminite macerals in all of the samples analysed.

ANALYTICAL METHODS

Vertical log profiles are used to illustrate variations in coal lithotype in the Hart seam cores, using the method of Marchioni (1980) (Fig. 2). The lithotype classification used to describe the cores is discussed in the following section.

Microscopic analyses were carried out on particulate coal pellets which were prepared as follows: large samples of coal were ground to -20 mesh size (850 μ m) and riffled to obtain representative sample splits of approximately 5g. These were ground on carborundum grits (400 grade followed by 600 grade) and then polished with a Metaserv automatic polisher using three grades of alumina (2 μ m, 0.1 μ m and 0.05 μ m) and water, on rotating selvyt cloth-covered laps.

Quantitative analyses were carried out by point-counting the coal macerals and mineral matter, according to the methods recommended by the International Committee for Coal Petrology (I.C.C.P., 1963), and using a Leitz 'Dialux' polarizing, incident-light microscope fitted with oil-immersion objectives and interchangeable fluorescent (blue-violet) and normal light sources. For low-rank coals, fluorescent light is best used to identify macerals of the liptinite group (Table 1)

Table 1. Maceral classification of brown coals and lignites (after International Committee for Coal Petrology, 1975).

Maceral Group	Maceral subgroup	Maceral	Maceral type	Maceral variety
Huminite	Humotelinite	Textinite		
		Ulminite	Texto-ulminite Eu-ulminite	A(dark) B(light)
	Humodetrinite	Attrinite Densinite		
	Humocollinite	Gelinite	Porigelinite Levigelite Phlobaphinite Pseudo-phlobaphinite	
		Corpohuminite		
		Sporinite Resinite Cutinite Alginite Liptodetrinite Suberinite Bituminite Fluorinite Exsudatinite Chlorophyllinite		
Liptinite				
Inertinite		Fusinite Semifusinite Macrinite Micrinite Inertodetrinite		

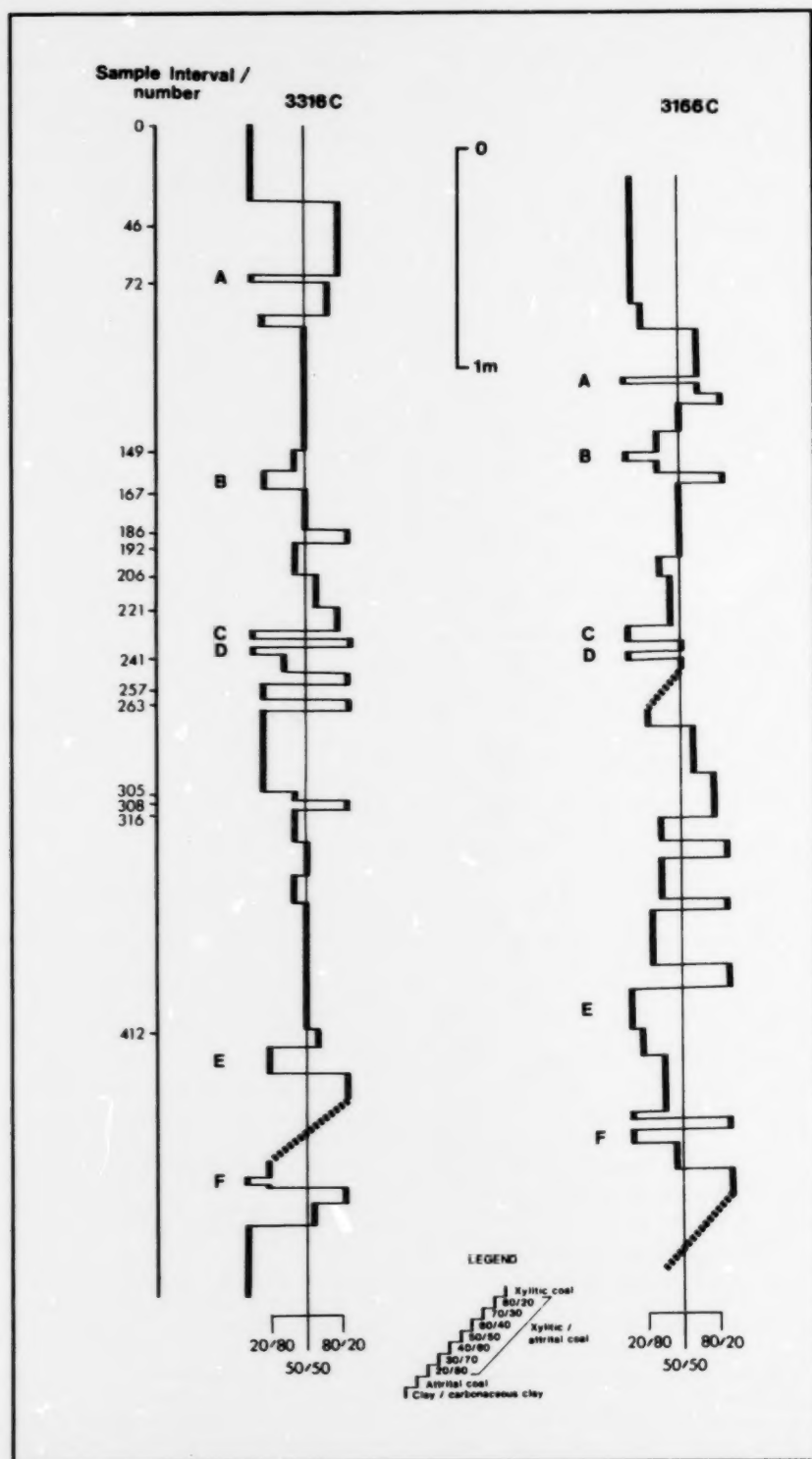


Figure 2. Lithotype log profiles of two cores from the Hart seam.

which appear dark grey to black in normal light and are weakly reflective. The macerals are identified according to the classification of I.C.C.P. (1971) for brown coal and lignite macerals (Table 1). The principal maceral groups are huminites, liptinites and inertinites. The huminites are reactive, the liptinites are hydrogen-rich and very reactive and the inertinites are variously reactive or semi-inert to inert in coal combustion, gasification, liquefaction and carbonization. Reflectance data (R_m) were obtained on all samples using a Leitz Orthoplan Pol-MPV II microscope-photometer system and standard conditions (546 nm, oil immersion).

LITHOTYPE CLASSIFICATION

Lithotype classifications used for banded (humic) bituminous coals are based on the nature of the banding and the relative brightness or lustre of the coal (I.C.C.P., 1963; Diessel, 1965; Cameron, 1978a). Low-rank humic coals are also banded but lack brightness, so other characteristics must be used as a basis for a lithotype classification.

Hagemann (1981) proposed a lithotype classification for European brown coals which he and others (Dobell et al, 1984) applied to Saskatchewan lignites. He proposed four lithotype-classes (pure coal: xylitic and non-xylitic; and impure coal: xylitic and non-xylitic) and recognized unbanded, moderately banded, banded and highly banded lithotypes. While the term xylitic adequately describes the woody-textured coal components, the authors feel that some description of the non-xylitic coal is required for lignites from Saskatchewan, and they desire a more detailed description of the banding since this might have far-reaching implications in terms of the coal reactivity. Use of the term attrital coal (Schopf, 1978) for the dull, massive, granular coal is preferred to non-xylitic. Banded coal is described as xylitic/attrital coal and the relative proportions of woody (xylitic) to granular (attrital) components are expressed as a ratio. The relationship between the xylitic and attrital components can be likened to that observed by Cohen and Spackman (1977) in peats from the Everglades-Mangrove complex of southern Florida; the xylitic components form a framework embedded in a matrix of attrital material.

Five lithotype groups are recognized:

- 1) **Xylitic coal** — woody textured or showing well preserved plant structures.
- 2) **Attrital coal** — massive, dull and granular.
- 3) **Xylitic/attrital coal** — banded coal with varieties described by the ratio of xylitic components embedded in an attrital matrix. For example, variety 70/30 is 70 per cent xylitic and 30 per cent attrital.
- 4) **Fibrous coal** — friable charcoal with a silky lustre.
- 5) **Impure coal** — coal rich in mineral inclusions.

In the Ravenscrag coals, attrital coal is dark brown to black in colour while xylitic coal varies from light brown to dark brown. Fibrous coal is a minor component in cores of the Hart seam; it occurs as small lenses (five to ten mm in length) and thin laminar inclusions (generally less than one mm thick) in the attrital matrix. These layers are difficult to recognize when the coal is wet, but when it is dry the coal tends to part at the fibrous layers. The tendency for coals to part at charcoal (fusain) layers was observed also by Cameron (1978a) in bituminous coals from southern Illinois.

The classification used here resembles that proposed by the International Committee for Coal Petrology (I.C.C.P., 1986) except that attrital coal (this classification) is considered as the lithotype group "attritic coal". Banded and unbanded varieties are recognized by the I.C.C.P. as individual lithotypes. They correspond to xylitic/attrital coal and attrital coal in this classification.

RESULTS AND DISCUSSION

LITHOTYPE ANALYSES

Lithotype log profiles for the Hart seam cores (3316C and 3166C) are illustrated in Figure 2. The relative abundance (percentages) of individual lithotypes in the two cores are given in Table 2. Clay/carbonaceous clay is inorganic material that occurs as partings within the seam, but floor- and roof-materials are excluded.

Table 2. Lithotype content of Hart seam cores, expressed as percentages.

Lithotype	Lithotype variety	3316C	3166C
Xylitic coal		10	12
	80/20	11	5
	70/30	3	6
	60/40	8	5
Xylitic/attrital coal	50/50	34	13
	40/60	11	8
	30/70	2	17
	20/80	19	10
Attrital coal		1	16
Fibrous coal		0	0
Clay/carbonaceous clay		1	8

In core 3166C, attrital coal and xylitic/attrital coal lithotype varieties 20/80, 30/70 and 40/60 account for 51 per cent of the 4.6 m. Core 3316C also contains lithotypes dominated by attrital components but xylitic components are more abundant than in 3166C. This results largely from abundance of 50/50 xylitic/attrital coal (34 per cent) in 3316C. Core 3316C also contains less clay/carbonaceous clay (1 per cent) than 3166C (8 per cent).

Vertical distribution of the coal lithotypes is not constant in the two cores, but some lithotypes and mineral partings, labelled A to F in Figure 2, can be correlated. In core 3166C, units A to F are inorganic (clay) partings, but in core 3316C units B and E consist of attrital coal. In both cores, unit D is a thin coal tonstein of unknown mineralogy which will be investigated by X-ray diffraction techniques.

Near the base of core 3166C, the coal tends to become more attrital from unit E to unit F; most of the corresponding interval is missing for core 3316C. The coal in the interval E to partings D and C is approximately the same thickness (1.7 m) in the two cores. In core 3316C, it has a relatively uniform composition consisting of 50/50 xylitic/attrital coal throughout the basal two-thirds of the interval and becomes more attrital toward the top. In core 3166C, the lower half of the E to D/C interval consists of lithotypes which alternate between 30/70 xylitic/attrital coal and xylitic coal, and the attrital component increases upward in the top half of the interval.

The interval D/C to B is the same thickness (0.3 m) in the two cores, but differs somewhat in lithology. In core 3166C, the coal is more xylitic beneath parting B whereas the xylitic component decreases immediately below the parting in core 3316C. In core 3316C, the interval B to A, consisting mainly of 50/50 xylitic/atritral coal, is 0.3 m thick. In core 3166C, the corresponding interval is only 0.15 m thick and contains a larger amount of xylitic components.

MACERAL ANALYSES

Hart seam

Maceral analyses, conducted on material from core 3316C, were carried out on 15 lithotypes ranging from xylitic coal to 20/80 xylitic/atritral coal (Table 3). The sample numbers correspond to the distance (in centimetres) from the top of the core (Fig. 2). The uppermost 36 cm of the core, consisting of clay/carbonaceous clay (roof) material, were not analysed.

Relative abundances of the huminite, inertinite and liptinite maceral groups are shown on a ternary diagram (Fig. 3). The

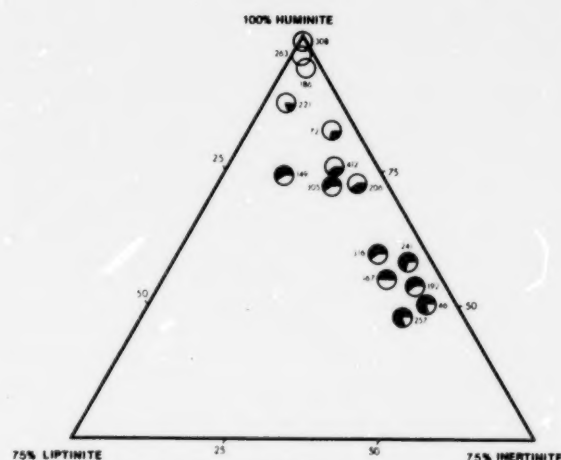


Figure 3. Ternary diagram showing the maceral composition (mmf) of coal samples from the Hart seam, Ravenscrag Formation.

Table 3. Maceral analyses of coal samples obtained from core (3316C) in the Hart seam, Ravenscrag Formation.

Maceral	Sample Numbers														
	46	257	241	316	149	192	305	167	206	412	72	221	186	263	308
Textinite	0	1	1	0	0	0	0	tr	0	0	0	0	0	0	0
Texto-ulminite	0	2	2	3	1	tr	4	1	1	2	1	1	0	2	1
Eu-ulminite A	23	17	26	25	27	34	38	34	47	38	61	48	68	65	76
Eu-ulminite B	2	tr	6	4	18	3	3	3	2	9	2	15	9	0	8
Cerpohuminit	2	2	3	3	6	3	8	3	5	7	7	7	13	16	11
Gelinite	2	6	3	2	0	2	2	3	1	1	2	1	0	0	0
Densinite	8	15	3	7	14	3	1	6	12	16	4	11	2	0	1
Attrinite	6	3	13	13	5	7	12	2	0	tr	1	0	0	4	0
Total Huminite	43	46	57	57	71	52	68	52	68	73	78	83	92	87	97
Sporinite	1	1	1	1	1	1	1	1	2	1	1	1	0	tr	0
Resinite	2	5	2	4	2	3	5	3	2	4	2	3	1	2	1
Alginite	0	1	0	tr	tr	0	tr	0	0	tr	0	0	0	0	0
Cutinite	0	0	0	tr	0	0	0	1	tr	0	0	0	0	0	0
Suberinite	0	0	0	1	1	0	0	tr	0	tr	0	tr	0	0	0
Fluorinite	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Bituminite	0	1	0	0	9	0	0	2	0	1	0	3	1	0	0
Exsudatinit	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Liptodetrinite	2	2	1	2	2	1	2	2	1	1	1	1	tr	tr	tr
Total Liptinite	5	10	4	8	15	5	8	9	5	7	4	8	2	2	1
Fusinite	10	12	9	11	2	16	3	9	6	4	3	1	1	tr	0
Semifusinite	8	13	15	6	3	8	2	10	5	4	3	1	1	0	tr
Macrinite	5	1	2	2	tr	3	2	2	2	1	2	0	0	0	0
Semimacrinite	4	4	3	2	1	3	3	2	2	2	1	0	0	tr	0
Sclerotinite	0	tr	0	0	0	0	0	0	0	0	0	0	0	0	0
Micrinite	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Inertodetrinite	12	11	8	10	4	10	7	11	6	6	4	1	1	1	1
Total Inertinite	39	41	37	31	10	40	17	34	21	17	13	3	3	1	1
Pyrite/Marcasite	4	1	0	0	1	0	0	0	0	0	0	0	tr	0	0
Other Mineral	10	2	2	4	3	2	6	4	5	2	6	5	2	8	2
Total Mineral	14	3	2	4	4	2	6	4	5	2	6	5	2	8	2

samples display variable maceral compositions. On a mineral-matter-free (mmf) basis, the lithotypes sampled consist of 47 to 99 per cent huminites, 1 to 45 per cent inertinites, and 2 to 16 per cent liptinites. Only one sample (149) contains abundant liptinites (16 per cent). Mineral matter ranges from 2 to 14 per cent. On the basis of the sampling methods used (selecting individual lithotypes), assessment of vertical variations in the maceral composition of the core was not possible.

Eu-ulminite A is the dominant humotelinite maceral in all samples; it is associated with eu-ulminite B, texto-ulminite and textinite (Table 3). Corpohuminites (2 to 17 per cent) is the most abundant humocollinite maceral in all but one sample (257); it is typically associated with humotelinite macerals and is present in variable amounts. Sample 263 contains as much as 17 per cent (mmf) corpohuminites. The humodetrinite macerals densinite and attrinite vary from 1 to 21 per cent (mmf). Fusinite, semifusinite and inertodetrinite are the most abundant inertinite macerals. Pyrolytic carbon, which is derived from organic material subjected to high temperatures, occurs in one sample (192). Pyrolytic carbon is present elsewhere in coal seams adjacent to igneous intrusions (Stach et al, 1982). Goodarzi (1985) described pyrolytic carbon in sub-bituminous coal from the Highvale Mine, Alberta and suggested that it may result from high temperatures encountered in peat- or swamp-fires.

Sporinite, resinite and liptodetrinite are the main liptinite macerals, except for sample 149 where the dominant liptinite maceral is bituminite (9 per cent).

Souris seam

Results of the maceral analyses on nine Souris seam samples are given in Table 4 and plotted on a ternary diagram (Fig. 4). Huminite, from 71 to 82 per cent (mmf), is the dominant maceral group for all samples. Within the huminite group, humocollinite is fairly constant at 4 to 10 per cent. Humodetrinite ranges from 20 to 36 per cent (mmf) and consists mainly of densinite. Humotelinite ranges from 33 to 54 per cent with eu-ulminite B the most common variety (23 to 51 per cent) followed by eu-ulminite A (4 to 9 per cent), texto-ulminite (0 to 4 per cent) and textinite (absent to trace).

Inertinites range from 5 to 19 per cent (mmf) in the Souris coal samples. Fusinite, semifusinite and inertodetrinite are the most common macerals with two per cent or less of macrinite, semimacrinite and sclerotinite. The inertinite content of the seam increases upwards in three of the four boreholes examined. Samples 82-54R 26, 82-57R 31, 82-61R 65 and 82-64R 40, from the upper parts of the seam, are inertinite-rich (Table 4). In the other borehole (82-57R), the inertinite content of the coal increases downwards.

Total liptinite ranges from 9 to 18 per cent (mmf) with sporinite, resinite and liptodetrinite among the most common macerals. Alginite has been tentatively identified in all samples; the internal structure is generally well preserved, and some may possibly be pollen rather than algal material (E.M.V. Nambudiri and L.D. Stasiuk, personal communication) so that the material should be classified as sporinite. Minor amounts of cutinite, suberinite, fluorinite and bituminite are present. Two samples (82-54R 30 and 82-61R 67) contain 12 and 14 per cent clay minerals (Table 4) which suggests that clay partings are included in the two samples.

CORRELATION BETWEEN LITHOTYPE AND MACERAL COMPOSITION

In the Hart seam, liptinites are minor components with a general range of 2 to 10 per cent (mmf) and an exceptional value of 16 per cent (mmf) for one sample (Table 3, Fig. 3). More than 90 per cent of the coal is generally composed of huminite and inertinite macerals so that the lithotype variations would be expected to reflect mainly the relative abundances of huminites and inertinites.

Percentages of huminite and inertinite macerals do indeed reflect variations in coal lithotype. The xylitic coal samples 186, 263 and 308 consistently contain more than 90 per cent huminites. Samples of xylitic/atritral coal 20/80 (samples 46 and 257) contain roughly equal amounts of huminite (43 to 46 per cent) and inertinite (39 to 41 per cent). The inertinite content of the coal increases significantly as the proportion of attrital material versus xylitic material increases (Fig. 5). Xylitic/atritral coal 20/80 and 30/70 both contain significantly more than 30 per cent inertinite. In the xylitic/atritral coal 40/60 and 50/50, the inertinite content ranges from 10 per cent to 40 per cent. The lowest inertinite value, found in sample 149 (10 per cent inertinites), is somewhat anomalous. With the exception of this value, the inertinite content increases fairly regularly as the banded lithotypes decrease and the attrital components increase (Fig. 5). Humodetrinite, which characteristically forms a matrix for other macerals, also increases as the amount of attrital coal increases. Humodetrinite accounts for less than 5 per cent of the xylitic coal but increases to a maximum of 20 per cent in the 40/60 xylitic/atritral coal (Fig. 5).

The lithotype divisions are based on the proportions of framework (100 per cent xylitic) to matrix (100 per cent attrital) coal. The xylitic coal is composed of more than one maceral (humotelinite, humocollinite) and the attrital coal is mainly humodetrinite, inertinite and liptinite. The lithotypes probably reflect coal maceral associations (microlithotypes) rather than individual macerals. Figure 6 shows the relationship between maceral subgroups and their associations

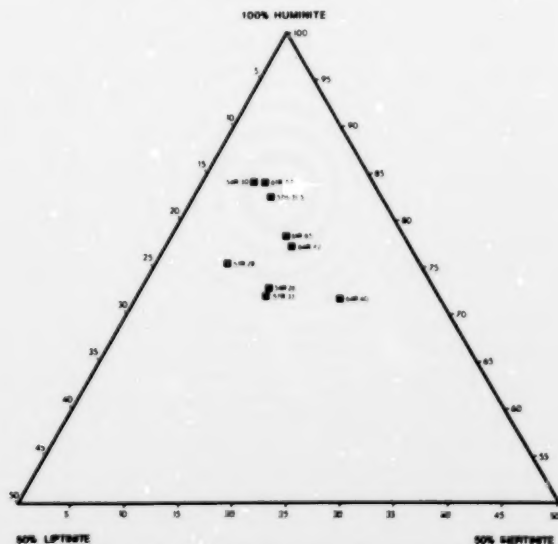


Figure 4. Ternary diagram showing the maceral composition (mmf) of coal samples from the Souris seam, Ravenscrag Formation.

(not formal microlithotypes) and the lithotypes. The second part (Phase 2) of this study will investigate relationships between lithotypes and microlithotypes.

ECONOMIC IMPORTANCE OF LITHOTYPE ANALYSIS

Macroscopic characteristics (lithotype) of the Hart coal correlate with the microscopic character (macerals), so that microscopic constitution can be predicted reasonably well by examining coal samples; for example, xylitic coal is found to be rich in humotelinite and humocollinite macerals. Petrographic studies of Ravenscrag coal (Energy Research Unit, 1980, 1981) have shown that the humotelinite and humocollinite are the most reactive of the huminite macerals in coal gasification. Liptinites are hydrogen-rich and highly desirable in coal liquefaction feedstocks but, in the Hart seam, liptinite contents are not easily determinable from lithotype variations. The humodetrinites are less reactive mainly because of the association with inertinites (Energy Research Unit, 1980, 1981). Inertinites, which do not liquefy or gasify easily, have a detrimental effect upon coal combustion; some inertinite macerals are difficult to burn in a pulverized fired

combustion system resulting in large amounts of unburned carbon in the fly ash (Pearson, 1985). Inertinites are abundant in xylitic/atritral coal with a large attrital component. On the basis of coal lithotype analysis, selection of coal suitable for combustion, liquefaction, gasification or briquetting might be feasible.

REFLECTANCE ANALYSES

The reflectance of huminite macerals has not been standardized as rank parameter for low-rank coal even though Cameron et al (1984) demonstrated reasonably good correlations between the reflectance of huminite macerals (eu-ulminite A and eu-ulminite B), and the volatile matter contents and calorific values of Greek lignites. The reflectance of the eu-ulminites can therefore be considered a reasonably good rank parameter for low-rank coals and can certainly be relied upon to evaluate coal rank on a comparative basis.

The mean reflectance values (per cent R_m) for the Hart seam samples (Table 5) are 0.21 per cent (eu-ulminite A) and 0.29 per cent (eu-ulminite B). Comparable values for the Souris

Table 4. Maceral analyses of coal samples obtained by reverse circulation drilling in the Souris seam, Ravenscrag Formation.

Maceral	Sample Numbers								
	(italicized numbers correspond to the distance in centimetres from the top of the core)								
	82-54R			82-57R		82-61R		82-64R	
	26	28	30	31	33	65	67	40	42
Textinite	0	0	0	0	0	0	0	tr	0
Texto-ulminite	1	1	1	4	1	tr	0	tr	tr
Eu-ulminite A	8	8	6	6	8	6	4	8	4
Eu-ulminite B	25	25	36	43	22	27	44	25	32
Corpohuminite	6	6	5	5	5	4	2	2	2
Gelinite	2	4	4	2	2	3	3	2	2
Densinite	27	27	22	19	30	34	19	29	33
Attrinite	0	0	0	0	0	0	0	0	0
Total Huminite	69	71	74	79	68	74	72	66	73
Sporinite	3	3	2	3	3	3	2	3	3
Resinite	2	2	1	2	2	2	2	2	2
Alginite	1	5	2	1	4	1	2	1	1
Cutinite	1	1	0	tr	1	0	tr	0	tr
Suberinite	1	0	1	0	0	0	tr	tr	1
Fluorinite	0	1	0	0	0	tr	0	0	tr
Bituminite	0	1	0	0	0	0	tr	0	0
Exsudatinite	0	0	0	0	0	0	0	0	0
Liptodetrinite	3	4	4	4	5	4	3	2	3
Total Liptinite	11	17	10	10	15	10	9	8	10
Fusinite	3	1	2	1	3	3	1	4	1
Semifusinite	3	1	1	2	1	2	2	5	2
Macrinite	1	1	tr	tr	2	1	tr	1	1
Semimacrinite	1	2	tr	1	1	1	1	1	2
Sclerotinite	1	0	0	tr	0	0	0	1	tr
Micrinite	0	0	0	0	0	0	0	0	0
Inertodetrinite	6	2	1	3	4	3	1	6	5
Total Inertinite	15	7	4	7	11	10	5	18	11
Pyrite/Marcasite	tr	tr	2	0	tr	0	2	1	tr
Other Mineral	6	6	10	3	5	6	12	6	6
Total Mineral	6	6	12	3	5	6	14	7	6

seam samples (Table 6) are 0.26 per cent (eu-ulminite A) and 0.34 per cent (eu-ulminite B).

The data show significant differences in rank of coals from the Hart and Souris seams. According to Hilt's law, coal rank should increase with depth in horizontal or gently dipping strata under normal geothermal conditions (Stach et al, 1982). The Souris seam is stratigraphically higher than the Hart seam, but is of higher rank. This is consistent with findings of Cameron and Marconi (1979). Two possible reasons for the difference in rank are:

- 1) the Souris seam coals were buried to much greater depth than they presently occupy, or
- 2) higher geothermal gradients have been associated with the Estevan area since the Paleocene.

CONCLUSIONS

The Hart seam is dominated by various types of banded xylitic/atritral coal consisting of woody (xylitic) components in a matrix of granular (atritral) material. The proportion of atrital material in the lithotypes generally increases beneath inorganic partings. The partings, along with a thin tonstein, can be correlated in the cores from wells 4.8 km apart. In both cores, the xylitic coal occurs only as a minor component (10 to 12 per cent). In core 3316C, the majority of the xylitic coal is concentrated in the middle of the seam, intercalated with partings of atrital-rich material; in core 3166C, the xylitic coal is distributed throughout the seam.

A strong relationship between maceral composition and lithotypes is demonstrated. The percentages of inertinite and humodetrinite are larger with increasing proportions of atrital

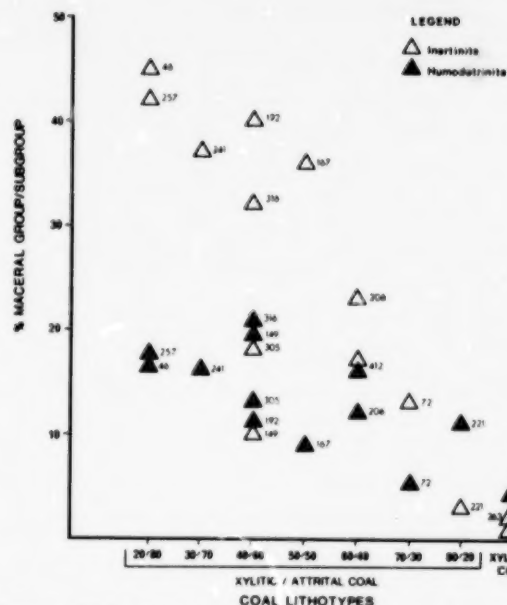


Figure 5. Relative abundances of inertinite and humodetrinite (mmf) in selected lithotypes from Hart seam cores.

material in the xylitic/atritral coal; conversely, the amount of humotelinite and humocollinite increases as the coal becomes more xylitic.

The Souris and Hart seams differ from one another in both rank and maceral composition. The Souris coals are richer in

Table 5. Reflectance data for coal samples from the Hart seam.

Coal seam	Sample	Per cent random reflectance (oil)					
		Eu-ulminite A			Eu-ulminite B		
		Mean	Sd.*	N.*	Mean	Sd.	N.
Hart	3316C 46	0.22	0.02	50	0.31	0.03	40
Hart	3316C 257	0.21	0.02	50	0.29	0.02	10
Hart	3316C 241	0.22	0.02	50	0.32	0.03	40
Hart	3316C 316	0.21	0.02	50	0.30	0.02	40
Hart	3316C 192	0.20	0.02	50	0.29	0.02	40
Hart	3316C 305	0.21	0.02	50	0.30	0.03	40
Hart	3316C 149	0.22	0.02	50	0.29	0.02	50
Hart	3316C 167	0.21	0.02	50	0.30	0.02	50
Hart	3316C 206	0.20	0.02	50	0.28	0.03	40
Hart	3316C 412	0.21	0.02	40	0.30	0.02	40
Hart	3316C 72	0.20	0.02	50	0.29	0.02	40
Hart	3316C 221	0.20	0.02	40	0.26	0.02	40
Hart	3316C 186	0.18	0.02	50	0.28	0.02	50
Hart	3316C 263	0.21	0.02	50	-	-	-
Hart	3316C 308	0.19	0.01	40	0.25	0.02	50

*Sd.: Standard deviation; N.: Number of measurements.

Table 6. Reflectance data for coal samples from the Souris seam.

Coal seam	Sample	Per cent random reflectance (oil)					
		Eu-ulminite A			Eu-ulminite B		
		Mean	Sd.*	N.*	Mean	Sd.	N.
Souris	82-54R 26	0.24	0.02	50	0.33	0.02	50
Souris	82-54R 28	0.25	0.03	50	0.33	0.03	50
Souris	82-54R 30	0.25	0.03	50	0.33	0.03	50
Souris	82-57R 31.5	0.27	0.02	50	0.34	0.03	50
Souris	82-57R 33	0.27	0.02	50	0.35	0.03	50
Souris	82-61R 65	0.25	0.02	50	0.34	0.03	50
Souris	82-61R 67	0.27	0.03	50	0.36	0.03	50
Souris	82-64R 40	0.26	0.02	50	0.34	0.03	50
Souris	82-64R 42	0.26	0.02	50	0.34	0.03	50

* Sd.: Standard deviation; N.: Number of measurements.

liptinites and poorer in inertinites than the Hart coals suggesting that they might be better suited for coal conversion. However, coal from the Hart seam which is abundant in xylitic and xylite-rich banded lithotypes could also be suitable for coal conversion. The Souris seam, although stratigraphically higher than the Hart seam, contains higher rank coal.

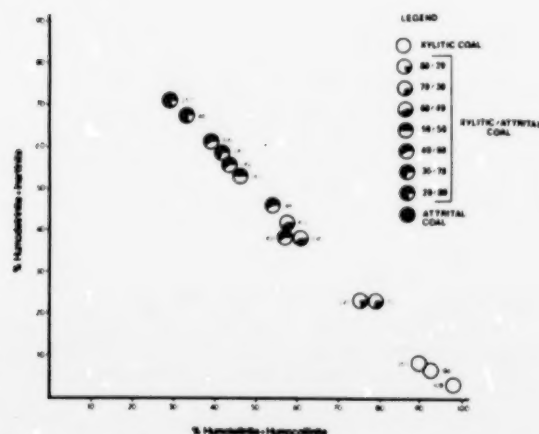


Figure 6. Relationships between macerals forming coal framework and matrix based on the maceral group/subgroup composition of selected lithotypes from the Hart seam.

REFERENCES

- Cameron, A.R., 1978a, Megascopic description of coal with particular reference to seams in southern Illinois, in R.R. Dutcher, ed., Field description of coal: American Society of Testing Materials Special Technical Publication 661, Philadelphia, p. 9-32.
- Cameron, A.R., 1978b, Petrographic characteristics of lignites from the Estevan area, in S. H. Whitaker, J.A. Irvine, and P.L. Broughton, Coal resources of southern Saskatchewan: a model for evaluation methodology: Geological Survey of Canada Economic Geology Report 30, 156 p.
- Cameron, A.R., and L.G. Marconi, 1979, Reflectance measurements on ulminite from Saskatchewan lignites (abstract): Geological Society of America Programs with Abstracts, v. 11, p. 397.
- Cameron, A.R., W.D. Kalkreuth, and C. Koukouzas, 1984, The petrology of Greek brown coals: International Journal of Coal Geology, v. 4, p. 173-207.
- Cohen, A.D., and W. Spackman, 1977, Phytogenic organic sediments and sedimentary environments in the Everglades-Mangrove complex: Palaeontographica, Abt. B, v. 161, 144 p.
- Diessel, C.F.K., 1965, Correlation of macro- and micropetrography of some New South Wales coals: Proceedings of the 8th Commonwealth Mining and Metallurgical Congress, v. 6, p. 669-677.
- Dobell, P., A.R. Cameron, and W.D. Kalkreuth, 1984, Petrographic examination of low-rank coals from Saskatchewan and British Columbia, Canada, including reflected and fluorescent light microscopy, SEM, and laboratory oxidation procedures: Canadian Journal of Earth Sciences, v. 21, p. 1209-1228.
- Energy, Mines and Resources Canada, 1982, Canada-coal map at 1:7,500,000, in The National Atlas of Canada, 5th edition: Geographical Surveys Directorate, Surveys and Mapping Branch, Energy, Mines and Resources Canada.

- Energy Research Unit, 1980, Petrographic analyses of coal feedstocks and residues: Report prepared for Energy, Mines and Resources Canada under Department of Supply and Services Contract No. OST79-00030.
- Energy Research Unit, 1981, Characterisation of solid residues from coal liquefaction processes: Report prepared for Energy, Mines and Resources Canada under Department of Supply and Services Contract No. OSU80-00088.
- Goodarzi, F., 1985, Optically anisotropic fragments in a western Canadian subbituminous coal: *Fuel*, v. 64, p. 1294-1300.
- Hagemann, H.W., 1981, Part I, Identification of lithotypes in lignites of southern Saskatchewan; Part II, Macroscopic examination and collecting samples from core stored at the Hat Creek Mine site, British Columbia: Geological Survey of Canada Open File Report, 67 p.
- International Committee for Coal Petrology, 1963, 1971, 1975, International handbook of coal petrology, 2nd edition, 1963; 1st supplement to 2nd edition, 1971; 2nd supplement to 2nd edition, 1975: Centre National de la Recherche Scientifique, Paris.
- International Committee for Coal Petrology, 1986, Lithotype classification for soft brown coals proposed at 39th annual meeting, Doncaster, U.K.
- Marchioni, D.L., 1980, Petrography and depositional environment of the Liddell seam, Upper Hunter Valley, New South Wales: *International Journal of Coal Geology*, v. 1, p. 35-61.
- Pearson, D.A., 1985, The quality of Canadian coal — a petrographic approach to its characterization and classifications, in T.H. Patching, ed., *Coal in Canada*, Canadian Institute of Mining and Metallurgy Special Volume 31, p. 21-30.
- Schopf, J.M., 1978, Further suggestions about coal description in the field, in R.R. Dutcher, ed., *Field description of coal: American Society of Testing Materials Special Technical Publication 661*, Philadelphia, p. 3-8.
- Stach, E., M.Th. Mackowsky, M. Teichmüller, G.H. Taylor, D. Chandra, and R. Teichmüller, 1982, *Stach's Textbook of Coal Petrology*, 3rd edition: Gebrüder Borntraeger, Stuttgart.
- Whitaker, S.H., J.A. Irvine, and P.L. Broughton, 1978, Coal resources of southern Saskatchewan: a model for evaluation methodology: Geological Survey of Canada Economic Report 30, 156 p.

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SODIUM SULPHATE DEPOSITS OF WESTERN CANADA: GEOLOGY, MINERALOGY, AND ORIGIN

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ABSTRACT

Sodium sulphate (Glauber's salt) is required in the pulp and paper industry and is also widely used in detergents as a replacement for phosphates. Future potential uses of this industrial mineral include solar energy storage and a glassmaking ingredient.

Worldwide, few commercial deposits of sodium sulphate are known. Western Canada has major accumulations of this commodity located mainly in southern Saskatchewan and eastern Alberta. Most of these deposits have formed in shallow ephemeral lakes that range in area from less than 1 km² to more than 300 km². The lake basins range in shape from small kettles to large cut-off riverine channels. Basin morphology is controlled mainly by the immediate postglacial history of the area.

In general, the postglacial sediment column within western Canadian deposits consists mostly of thick-bedded mirabilite and thenardite crystals with variable amounts of other evaporite minerals (bloedite, epsomite, natron), organic debris, and clay- to gravel-sized clastic material. The mirabilite is both endogenic and authigenic in origin, having precipitated from intermittent supersaturated surface brines as well as from pore waters. Variations in mineralogy and brine chemistry occur between basins and, through time, within a single basin.

The stratigraphic sequence within a deposit is generally complex. Lateral facies changes and post-depositional processes — including solution and reprecipitation of the crystal bed, salt karsting, and mud diapirism — may considerably modify the sedimentary record and, therefore, the economic potential of individual basins.

The origin and evolution of these deposits is still problematic, and numerous theories have been proposed to account for their unique characteristics. Their chemistry is likely due to a complex series of reactions including cation exchange, sulphide oxidation, sulphate reduction, and dissolution of subsurface evaporite and carbonate bedrock by circulating groundwater. These playa basins are, however, just one stage in an evolutionary spectrum which also includes the deeper saline lakes of the region.

INTRODUCTION

The Northern Great Plains area has been an important source of sodium sulphate for over sixty-five years. Some of the earliest industrial efforts in the Northern Plains region were centred on salt extraction from alkaline sloughs and lakes of southern Saskatchewan. Total composite reserves for this region are among the largest in the world (Weisman and Tandy, 1975). Presently, about 400,000 tonnes of sodium sulphate are produced per year from seven "active" deposits. The total annual value of this product normally exceeds \$30 million making this region the world's leading producer.

Despite the economic importance, until recently very little sedimentological or geochemical data have been collected, and essentially no stratigraphic information about the deposits exists. Knowledge of the sedimentary processes, mineralogy, and post-depositional alterations is essential to assess the potential of the resource and to evaluate both the short-term changes and long-term evolution of the depositional system.

Investigation of these deposits is important for several additional reasons:

- 1) Saline and hypersaline lacustrine environments are amongst the least understood depositional regimes in sedimentary geology. A study of the evaporite mineralogy and its relation to basin morphology, hydrochemistry, and brine evolution will do much to advance our knowledge of terrestrial evaporite sequences. Theoretical models of these sequences are becoming increasingly important in both the petroleum and mineral exploration industries.
- 2) Diagenetic reactions involving the precipitated evaporite minerals and clastic grains are very important in the generation of other saline minerals, authigenic silicates (such as zeolites and clay minerals) and carbonates. Details of these reactions are poorly known and infrequently studied.
- 3) Sediments in the playas are sensitive indicators of changes in the hydrologic budget within each

drainage basin. Thus, the stratigraphic record in the lakes should reflect both short-term and long-term climatic fluctuations.

- 4) Elevated levels of base metals such as copper, zinc and lead are present in the sediments of several of these deposits. Mining and extraction of the salts can mobilize these elements, thereby creating a potential environmental problem.

The purposes of this paper are:

- 1) to review the general geological and hydrological setting of the sodium sulphate deposits,
- 2) to discuss briefly the modern sedimentary processes operating in the basins,
- 3) to discuss the mineralogy and geochemistry of the deposits, and
- 4) to examine the origin and evolution of selected deposits as suggested by the sedimentary fill in representative basins.

REGIONAL SETTING

TOPOGRAPHY, CLIMATE, HYDROLOGY

The sulphate deposits discussed in this paper occur in the Great Plains physiographic province of North America (Fig. 1). This region is characterized by hummocky to gently rolling topography interspersed with numerous deep, commonly terraced valleys that have been cut by glacial meltwater. The Missouri Coteau, a distinct 50- to 100-km-wide band of knob and kettle topography, is the dominant geomorphic feature of the area.

In general, the Northern Great Plains experience a cold continental, semi-arid climate. Stable high-pressure continental and Arctic air masses dominate during the winter months giving the region prevailing cold, clear weather. Continental and Polar air masses also dominate the summer weather resulting in warm and dry conditions. The region is south of the main paths of winter and summer low-pressure systems, but pressure and temperature gradients associated with these systems cause the area to be frequently swept by strong winds. The mean daily temperature during January over most of the region is about -17°C ; during July it is 20°C . A most important characteristic of the region is the extreme variability of diurnal, seasonal and annual temperatures. This variability significantly affects many chemical and physical processes of the salt lakes of the region; it is also integral to the unique production techniques used by most of the sulphate operators.

Another important climatic factor influencing the region is the high ratio of evaporation to precipitation. The mean annual precipitation is about 30 cm; however, more than 125 cm of water may be lost per year through evaporation from open-water bodies (CNC/IHD, 1978).

Large areas of the Northern Great Plains are characterized by internal drainage (Fig. 1). Because of its lack of integrated drainage, the Missouri Coteau has many individual closed basins, most of which contain salt lakes. Other large areas of internal drainage exist in central and western Saskatchewan and eastern Alberta. Taken together, the basins comprise one of the largest areas of closed drainage in North America.

BEDROCK AND GLACIAL GEOLOGY

The Northern Plains are underlain by nearly horizontal Phanerozoic sedimentary rocks up to 4000 m thick. The Paleozoic section consists mainly of a series of stacked carbonate-evaporite cycles whereas the overlying Mesozoic

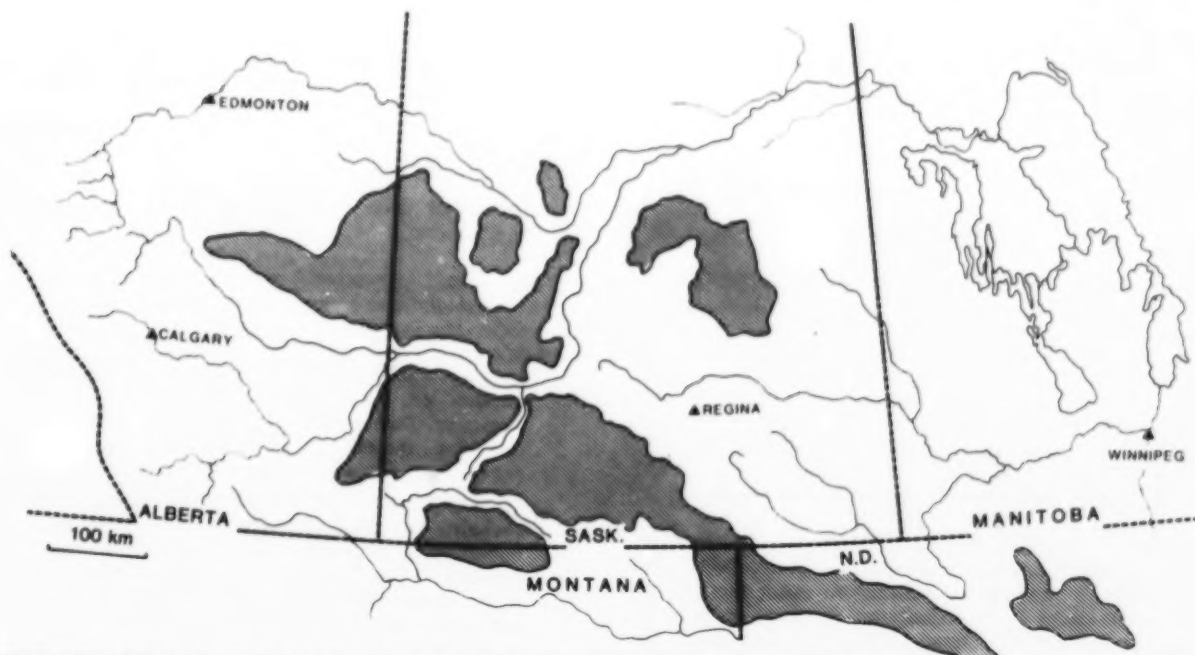


Figure 1. Map of the Northern Great Plains region of North America; shaded areas represent internal drainage basins in which most salt lakes and sodium sulphate deposits of the region are situated. North is toward the top of the map.

and Cenozoic strata are dominantly sand-shale sequences. Dissolution of the highly soluble Paleozoic evaporites by groundwater has created localized collapse structures over much of the area (Christiansen, 1967a, 1971), modifying the relatively simple structural relationships of the flat-lying formations. Grossman (1968) maintained that this evaporite dissolution provided a source of ions for the many salt lakes of the region.

The bedrock surface was strongly modified by preglacial fluvial erosion (Whitaker and Pearson, 1972), and by the start of the Quaternary Period, a mature dendritic drainage pattern had been established over much of the Northern Plains (Stalker, 1961; Christiansen, 1967b). In general, this ancestral pattern is reflected by today's streams, except that much of the upper Missouri River originally flowed northeast into Hudson Bay rather than into the Mississippi River basin (Meneley et al, 1957).

The bedrock of the region is mantled by as much as 300 m of unconsolidated Quaternary sediment, mainly till and glaciofluvial sands and gravels. During deglaciation, meltwater from the retreating glacier carved numerous ice-marginal channels and spillways in the sediment (Christiansen, 1979). Although now abandoned or buried under more recent sediment, many of these valleys are sites of salt lakes. The hydrogeological properties of the Quaternary sediments control both the direction of flow and the quantity of groundwater discharge, and these factors influence the location and development of the salt lakes (Last and Schweyen, 1983).

ORIGIN OF THE BASINS

Unlike many other playas and salt lakes of the world, the sodium sulphate-rich basins in the Northern Great Plains are not mainly a result of tectonism or deflation. Rather, they occur in closed depressions that were created within the past 20,000 years through glacial activity. Three basic types of basins are recognizable:

- 1) channel/riverine basins;
- 2) roughly circular "sinkhole" basins or doughnuts; and
- 3) broad, flat depressions with no distinctive morphological character.

Combinations and gradations between each type are common.

Most sodium sulphate deposits of the region occupy basins that are distinctly of riverine origin, created when meltwater cut a channel into glacial material during or immediately after recession of the Wisconsin ice sheet between 17,000 and 13,000 years ago. Such basins are generally floored by well sorted gravels and sands, whereas the channel banks are normally composed of till. Closure of the basin is generally the result of a debris slide or progradation of incipient alluvial fans across the channel. In north-trending channel basins, isostatic crustal rebound provided a closure mechanism by raising the southern end of the basin more than the northern end.

In areas of former glacial ice stagnation, such as the Missouri Coteau, depressions formed by melting of buried ice are the dominant basin type. The kettles tend to be small and circular, but some have great thicknesses of postglacial clastics and salt.

For example, the Ingebrigt deposit in southwestern Saskatchewan contains up to 50 m of salt in an area of less than 0.5 km² (Rueffel, 1968).

Finally, some of the lakes are remnants of much larger postglacial or ice-marginal lakes. These basins are simply low spots in the till and associated glacial sediments and are usually surrounded by old strandlines and lacustrine sediments. Some lake basins are very large (greater than 300 km² in area), with most of the salt reserve held as dissolved ions in the brine.

All of the basins from which salt is commercially produced, and most lakes that contain abundant sodium sulphate, are shallow "playa" lakes. Very few lakes which contain appreciable amounts of sodium sulphate are deep-water basins.

ECONOMIC GEOLOGY

Commercial exploitation of the saline lakes in the region began in 1918 with the extraction of magnesium and sodium sulphates and carbonates from Muskiki Lake, near Saskatoon. Production of anhydrous sodium sulphate (salt cake) from some 20 different lakes gradually increased over the next five decades to a high of approximately 700,000 tonnes in 1973 (Figs. 2 and 3). Today, this region supplies nearly 50 per cent of the total North American demand for sodium sulphate with the rest obtained from deposits in the southwestern United States and as by-products from various manufacturing processes. A tremendous increase in the price of salt cake during 1973-75 (from \$15 to \$48/tonne) and again during 1980-83 (from \$62 to \$108/tonne) led to renewed interest in leasing and mining activities in the region during these periods. Despite softening markets and production declines during the past several years, over \$30 million-worth of sodium sulphate is produced annually from salt lakes in Saskatchewan and Alberta.

Historically, the two largest uses of sodium sulphate have been in producing kraft paper and allied products, and in the manufacture of detergents (Broughton, 1984). More recently, however, the energy industry has been using large amounts of the salt as a conditioner to facilitate fly-ash suppression in coal-burning power plants (Tremblay, 1984). Another new use of salt cake is in the manufacture of potassium sulphate by the reaction of Na₂SO₄ with KCl (Barry, 1986; Barry et al, 1985). Other potentially significant applications include use in glass, ceramic, and paint manufacture, and for storage of solar energy.

The sodium sulphate industry in this region is based on reserves of three basic types:

- 1) sodium sulphate dissolved in brines that fill the saline lake basins,
- 2) the hydrated sodium sulphate mineral, mirabilite (Na₂SO₄·10H₂O), which occurs seasonally on the floor of the salt lakes due to precipitation within the overlying water column, and
- 3) the bedded salts, composed mainly of mirabilite and thenardite (Na₂SO₄), which make up the postglacial sedimentary fill in some basins.

Each of these three sources has been exploited during the past, but most current production is from hypersaline lake waters

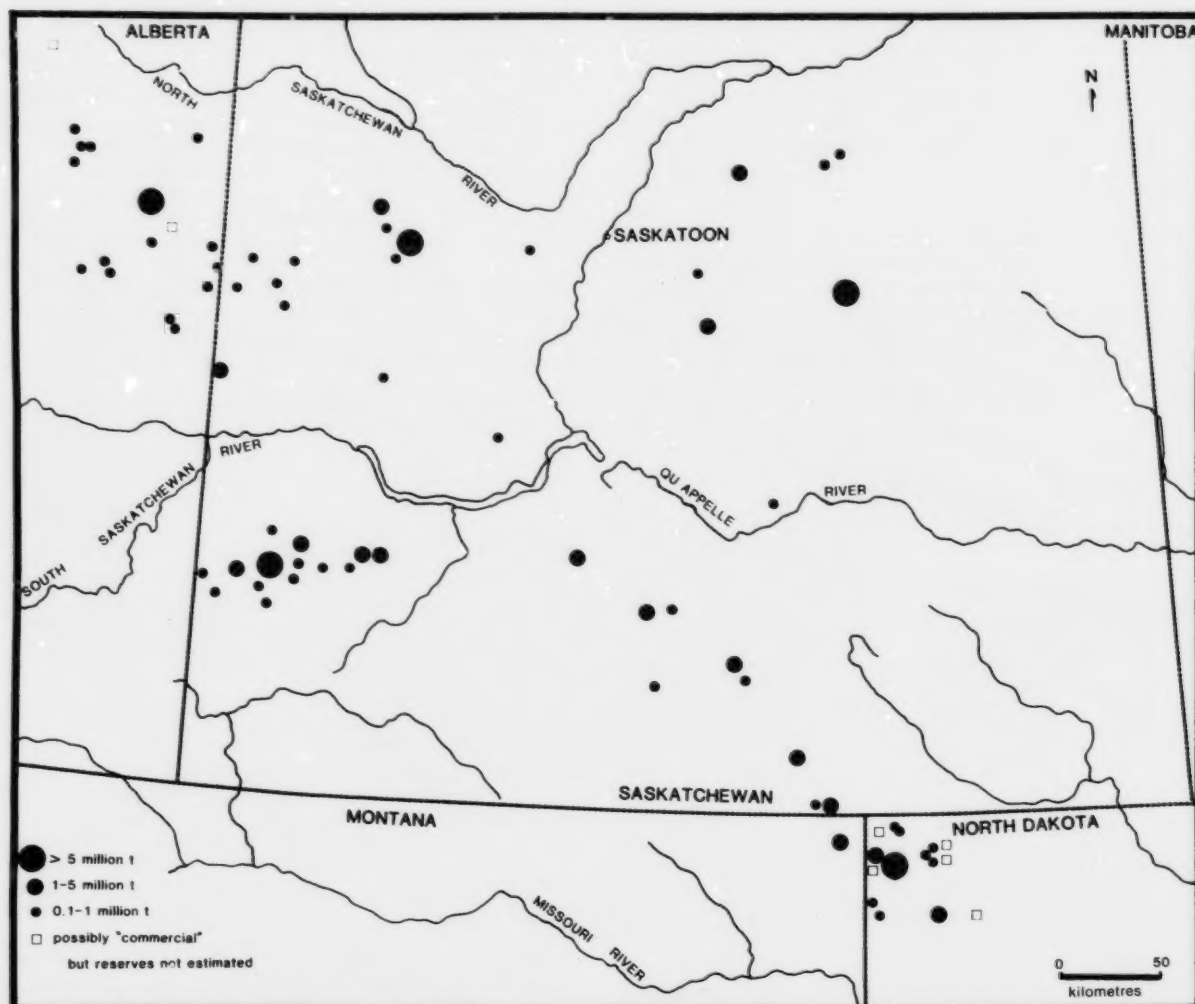


Figure 2. Map showing the distribution and size of sodium sulphate deposits of the Northern Great Plains.

which are pumped from the basin into holding reservoirs. Upon further concentration by evaporation during summer followed by cooling during the fall season, relatively pure mirabilite (Glauber's salt) is precipitated from the solution. The overlying brine is then drained back into the lake basin, and the salt is removed and stockpiled. Solution mining using hot water (MacWilliams and Reynolds, 1973) and dredge mining of permanent salt beds have also been practised.

The harvested Glauber's salt must be dehydrated prior to marketing. Methods for this processing vary considerably and are reviewed in detail by Weisman and Tandy (1975), Broughton (1984), and Rueffel (1968). Most producers simply raise the temperature of the salt to above its fusion point (about 32°C), and then either continue heating to evaporate the water of crystallization or remove the solid anhydrous precipitate from the slurry.

HYDROCHEMISTRY

As with most playa and intermittent lakes of the region, brine chemistry of the shallow sodium sulphate salt lakes varies

considerably both spatially and temporally. In their natural state, the brines are hypersaline and usually dominated by sodium, magnesium, and sulphate ions. Seasonal variation in salinity is related to seasonal variations of evaporation, precipitation, snow melt, and runoff. Relatively dilute inflow from melting snow and rainfall quickly dissolves the very soluble sodium and magnesium salts which were precipitated during the previous dry episode. By mid-summer, salinities of at least 150 ppt have been attained in most lakes. Evaporation losses during late summer and fall further concentrate the brine, with salinities normally exceeding 300 ppt.

Because the dilute inflow waters are relatively rich in calcium and bicarbonate ions, during the early spring the lakes may contain large amounts of Ca and HCO_3 . With increasing concentration, calcium and bicarbonate are lost through mineral precipitation, and the remaining brine becomes enriched in Na-Mg-SO₄-Cl. During the latter stages of desiccation massive quantities of sodium salts are precipitated, thereby leaving a Mg-Cl(SO₄)-rich brine.

The brine chemistries of the deeper, perennial sulphate-rich lakes are more stable on a seasonal basis, but are complicated

by density stratification. For example, Freefight Lake, a 24 m-deep basin in southwestern Saskatchewan, has a thin (5 m) layer of relatively dilute brine (75 to 100 ppt) overlying a much more saline (170 ppt) Na-Mg-SO₄-rich water column. Because of the striking contrast in specific gravities (1.07 versus 1.18), the two water masses do not mix. The relatively dilute upper layer undergoes considerable seasonal variation due to runoff and evaporation, temperature fluctuations, and biological activity. The dense lower water mass, however, is always at or near saturation with respect to several sodium and magnesium salts and shows little chemical variation on a seasonal basis.

Spatial variation in water chemistry is most common in large, riverine basins. Even during very windy periods, water circulation is commonly restricted resulting in salinity and ion-ratio gradients from one end of the basin to the other (see Figure 6 in Last, 1984).

The origin and ultimate source of the ions in these lakes have been the subject of considerable discussion in the scientific literature. As summarized by Sloan (1972, p. C22): "Many observations about the occurrence of the salts are valid, but interpretations of their genesis have generally been needlessly complex and unsubstantiated by the observed facts." Certainly much of the high salinity of the seasonally ponded brines is derived from dissolution of previously precipitated salts by the relatively dilute inflow. Groundwater also likely plays a major role in supplying ions to the basins; however, to date this groundwater contribution has not been adequately documented. Many researchers (e.g. Rueffel, 1968; Grossman, 1968; Freeze, 1969) have stressed the close association of major sulphate deposits with buried preglacial valleys, and have concluded that the buried valleys act as conduits for groundwater supplying dissolved components to the lakes. The ultimate source of the ions remains an unanswered question.

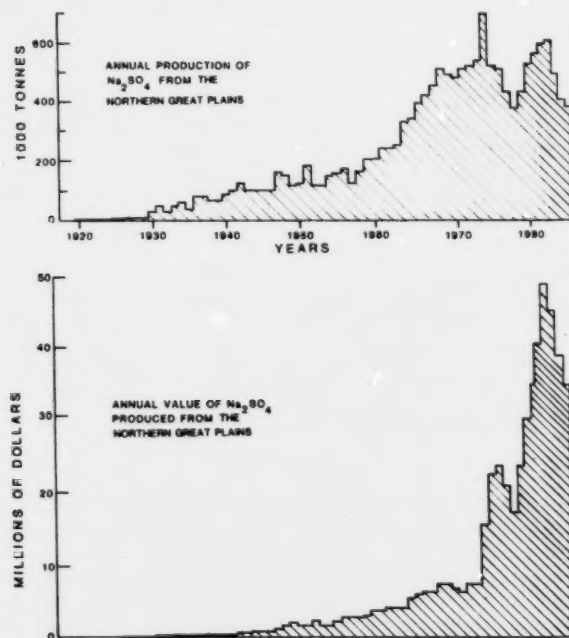


Figure 3. Annual production and value of sodium sulphate produced in Saskatchewan and Alberta, 1918 to present.

Paleozoic evaporites are known to have been extensively dissolved by circulating groundwater but are an unlikely source because of their incompatible brine chemistry (Fig. 4). The oxidation of pyrite in Cretaceous shales and the dissolution of gypsum in till and bedrock provide possible sources of sulphate (Wallick and Krouse, 1977). However, the complicated fractionation characteristics of the sulphur in sedimentary sulphates and sulphides and presence of sulphate-reducing bacteria make quantitative investigations of this suggestion very difficult.

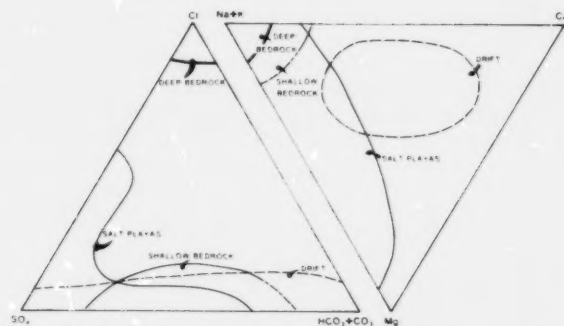


Figure 4. Triangular diagrams showing water-composition variation (in per cent equivalents) of the salt plays, drift groundwater, shallow (Cretaceous) bedrock groundwater and deep (Paleozoic) bedrock groundwater in western Saskatchewan (compiled from numerous sources).

MINERALOGY

The salt lakes of the Northern Great Plains contain a wide variety of minerals (Table 1). Most simply, the minerals can be grouped on the basis of origin into endogenic/authigenic precipitates and clastic detrital material.

Endogenic and authigenic precipitates vary in quantity and mineralogy depending on the precise surface-brine chemistry, groundwater composition, and hydrologic setting of the basin. The most common salts are mirabilite, thenardite and bloedite, with lesser amounts of kieserite, epsomite, burkeite, hexahydrate and halite.

These salts are clear to white, and are commonly coarsely crystalline. They occur in a wide variety of habits and morphologies.

In addition to these very soluble evaporitic salts, somewhat less soluble sulphates, sulphides, carbonates, and silicates are present. They include: gypsum, protodolomite, nesquehonite, huntite, natron, trona, magnesite, pyrite, and mixed-layer clays. These latter precipitates are commonly fine grained and generally occur as authigenic components in the muds of the basins. Some lakes also contain relatively rare sedimentary minerals such as scarbroite (Egan, 1986) dawsonite, and hydrohalite.

The detrital component of lacustrine sediments closely reflects the composition of the surrounding glacial material: clay minerals (mainly illite and smectite), dolomite, calcite, quartz, and feldspars (Egan, 1984). In deposits which are actively being mined, this clastic material usually comprises the bulk of the "modern" sediment. As the soluble sodium sulphate is extracted in mining operations, a layer of this insoluble residue blankets the deposit and greatly reduces the efficiency of the brining-extractor process.

MODERN SEDIMENTARY FACIES

GENERAL

Approximately seventy lakes contain economically extractable amounts of Na_2SO_4 , either as dissolved constituents in the brine or as permanent salt within the sedimentary fill. Most of our knowledge of the sediments and sedimentary processes operating in these sodium sulphate-rich lakes comes from study of the shallow playa basins, which form one end member of a continuum of basin-types in the Great Plains. Unfortunately, our understanding of the deeper, perennial sulphate lakes is inadequate.

Table 1. Mineralogy of saline playas of the Northern Great Plains. Minerals in upper-case indicate common occurrence.

CARBONATES

Aragonite CaCO_3
 CALCITE CaCO_3
 MAGNESIAN CALCITE CaCO_3
 DOLOMITE $\text{CaMg}(\text{CO}_3)_2$
 Protodolomite $\text{CaMg}(\text{CO}_3)_2$
 Nesquehonite $\text{Mg}(\text{HCO}_3)(\text{CO}_3)_2$
 Huntite $\text{CaMg}_3(\text{CO}_3)_4$
 Natron $\text{Na}_2\text{CO}_3 \cdot 10\text{H}_2\text{O}$
 Trona $\text{NaHCO}_3 \cdot \text{Na}_2\text{CO}_3 \cdot 2\text{H}_2\text{O}$
 Siderite FeCO_3
 Scarbroite $\text{Al}_2(\text{CO}_3)_3 \cdot 13\text{Al}(\text{OH})_3$
 Dawsonite $\text{NaAl}(\text{CO}_3)(\text{OH})_2$

SULPHATES, SULPHIDES, AND CHLORIDES

GYPSUM $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$
 MIRABILITE $\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$
 THENARDITE Na_2SO_4
 BLOEDITE $\text{Na}_2\text{Mg}(\text{SO}_4)_2 \cdot 15\text{H}_2\text{O}$
 Loewite $\text{Na}_2\text{Mg}_2(\text{SO}_4)_3 \cdot 15\text{H}_2\text{O}$
 Kieserite $\text{MgSO}_4 \cdot \text{H}_2\text{O}$
 Epsomite $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$
 Burkeite $\text{Na}_2\text{CO}_3 \cdot 2\text{Na}_2\text{SO}_4$
 Hexahydrite $\text{MgSO}_4 \cdot 6\text{H}_2\text{O}$
 D'Ansite $\text{Na}_2\text{Mg}(\text{SO}_4)_2 \cdot \text{Cl}$
 Halite NaCl
 Hydrohalite $\text{NaCl} \cdot 2\text{H}_2\text{O}$
 Jarosite $\text{KFe}_3(\text{SO}_4)_2(\text{OH})_6$
 PYRITE FeS_2

SILICATES AND OXIDES

QUARTZ SiO_2
 FELDSPARS K-Na-Ca aluminosilicates
 Sepiolite $\text{Mg}_3\text{Si}_4\text{O}_{10}(\text{OH})_2 \cdot \text{H}_2\text{O}$
 Zircon ZrSiO_4
 Halloysite $\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_3$
 Hornblende $\text{Ca}_2(\text{Mg}, \text{Fe})_2\text{Al}(\text{Si}, \text{Al})_7\text{O}_{22}(\text{OH}, \text{F})_2$
 KAOLINITE $\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_3$
 ILLITE Hydrated K-Mg-Fe aluminosilicate
 SMECTITE Hydrated Mg-Fe aluminosilicate
 MIXED-LAYER CLAYS variable
 Chlorite $(\text{Fe}, \text{Mg})_3\text{Al}_2\text{Si}_4\text{O}_{10}(\text{OH})_2$
 Muscovite $\text{K}_2\text{Al}_2\text{Si}_4\text{Al}_2\text{O}_{10}(\text{OH}, \text{F})_2$
 Norstrandite $\text{Al}(\text{OH})_3$
 Goethite $\text{FeO}(\text{OH})$
 Diaspore $\text{AlO}(\text{OH})$

DESCRIPTION OF MODERN SEDIMENTS

In their natural state, the near-surface (modern) sediments of the playas consist largely of very soluble sodium and magnesium evaporitic salts, with subordinate amounts of sparingly soluble carbonates and sulphates, clastic material, and organic detritus (Fig. 5). Several major environmental zones are easily recognized in most of the basins; these give rise to distinct sedimentary facies which are mappable on the basis of texture, mineralogy, organic content, evaporite-to-clastic ratio, and crystal morphology. The facies belts are generally similar to those identified in saline playa environments elsewhere (e.g. Hardie et al, 1978). Facies boundaries are commonly gradational.

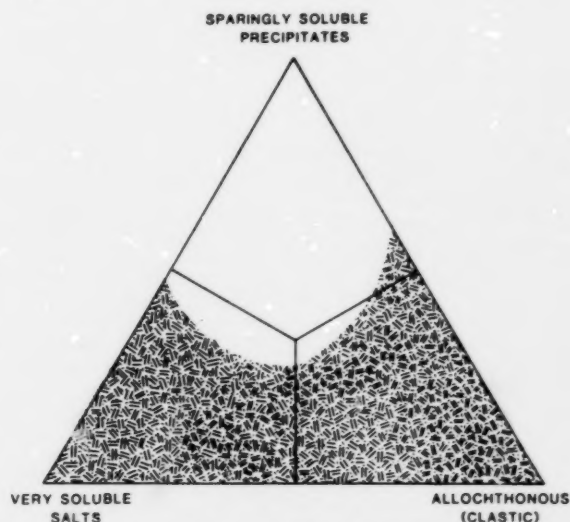


Figure 5. Triangular diagram of main sediment types; shaded area shows the compositional range of modern sediments in the salt playas of the Northern Great Plains (modified from Last, 1984).

Most of the lakes occupy steep-sided, riverine troughs so that the basin margins are dominated by poorly sorted colluvial and sheetwash sediments that slope down to meet broad mudflats and sandflats. Classic alluvial fans are absent and strandline features such as beaches or dunes are rare. The mudflats and sandflats are periodically covered by lake water and are usually saturated with brine throughout the year. Exposed mudflats usually become encrusted with white, finely crystalline efflorescent salt crusts formed by the evaporation of brine films brought to the surface by capillary action and evaporative pumping. Wind plays an important role in eroding and transporting salts from these dried crusts. The mudflats are also areas of massive intrasedimentary crystallization of salts resulting in destruction of lamination.

Mudflats and sandflats grade basinwards into salt pans. This is the most dynamic zone of the basin in terms of sedimentary processes. Surface runoff and, possibly, groundwater discharge contribute water that is ponded in salt-pan zones for time periods varying in length from several weeks to several months. Brine concentration is increased by dissolution of previously deposited salts and by evaporation throughout the season. Eventually, the brine becomes supersaturated and

precipitates a variety of evaporite minerals. Nucleation and precipitation of salts occur in several forms and at several sites:

- 1) at the surface of the brine in the form of hopper-shaped crystals which may coalesce to form large floating crystal-rafts, and
- 2) at the sediment-water interface in the form of rounded accretionary grains (termed "mirabolites") or large (up to two metres in length), euhedral bladed to tabular crystals and massive crystalline aggregates.

SUBSURFACE SEDIMENTS

STRATIGRAPHY

No two playa basins in this broad geographic region are stratigraphically identical. Certain stratigraphic associations are recurrent, however, and a generalized evolutionary pattern is apparent in the twelve salt playas currently under study.

Six broad lithostratigraphic units have been identified in basins in which full postglacial sequences have been preserved. In basins which are being altered by mining operations or by other post-depositional destructive phenomena (such as salt dissolution), one or more of these units may be missing.

- 1) **Till.** The lowermost sediment penetrated in most of the basins is a gravelly clay loam diamicton. The poor sorting and nonlaminated nature of this material suggest that it was ice-laid. Similar sediment commonly underlies present-day colluvium and soils on the slopes of the basins.
- 2) **Coarse sand and gravel.** In general, sediments of this unit directly overlie the basal diamicton. They are mostly brown to tan, well sorted, coarse grained, and contain little organic matter. This unit exceeds five metres in thickness in some basins. It generally pinches out toward the margins of the basin.
- 3) **Calcareous clay and silt.** This unit consists of grey to greenish grey clay and silt. Although not a marl, the sediment may have up to 30 per cent calcareous material, most of which is bioclastic calcite and aragonite, consisting of fragments of ostracods, gastropods, and *Chara*. The unit may also contain some tufa, irregularly spaced carbonate hardgrounds and crusts, and gypsum laminae. It is generally less than one metre thick.
- 4) **Black mud.** Sediments of this unit are black to very dark green, anoxic, fine-grained sands, silts and clays. High moisture contents of 50-80 per cent generally prohibit good core recovery. Organic contents, too, may be high; if so, the sediments are likely to have a strong smell of H_2S . Intrasedimentary crystals of mirabilite, thenardite, and gypsum are abundant.

This unit generally directly underlies, and interfingers with, the salt unit, and may be traced laterally into the modern mudflats/sandflats facies of the nearshore complex. Thickness ranges from one-half to three metres. Elevated levels of Cu and Zn have been recorded (Last, 1984).

- 5) **Salt.** Volumetrically, this is commonly the most abundant postglacial sediment within the salt playas.

Like modern salt-pan sediments, it is composed mainly of mirabilite and thenardite, but also contains appreciable amounts of gypsum, bloedite, and epsomite. Natron and halite occur in trace amounts. In several of the basins studied to date (Ceylon, Lydden and Chain Lakes), the proportion of mirabilite and thenardite decreases upwards in the section from about 80 per cent to 60 per cent of the soluble salt fraction. In contrast, the amount of Mg-bearing salts increases from less than 5 per cent at the base to as much as 20 per cent near the top of the section. The salt is coarsely crystalline and massive. In some deposits, the salt unit is remarkably pure with little insoluble material. In other basins, it shows considerable interbedding with black muds. As shown by Cole (1926), the total salt thickness ranges from less than one metre to nearly fifty metres.

- 6) **Clay and salt.** The uppermost five to fifty centimetres of sediment in most basins consist of black to greenish grey, silty clay and salt. This material is generally soft and has a very high water content, but may become well consolidated upon exposure and desiccation. As shown by Last (1984), this upper unit is usually distinctly laminated due to crystal morphology and mineralogical layering. Commonly, very large salt crystals and crystalline aggregates are present.

POST-DEPOSITIONAL MODIFICATION

In addition to sedimentological control, post-depositional processes are important in influencing the type, distribution, and occurrence of sediment in these basins. The additional controls are:

- 1) salt karsting and infilling of solution chimneys, and
- 2) mud diapirism.

In some places, these processes significantly disrupt large sections of the postglacial sediment-fill in the basin, thereby creating difficulties in some mining operations and in using a recovered stratigraphic sequence as a paleoenvironmental tool (Slezak and Last, 1985).

Salt karsting. Dissolution of soluble crystal beds in salt playas by relatively dilute groundwater creates local solution pits or chimneys in the salt unit. Seven such chimneys have been identified in the Ceylon Lake Basin; three in Lydden Lake, and two in Vincent Lake. In addition, Cole (1926) reported numerous "mud holes and chimneys" from Snakehole, Muskiki, Ingebrigt, Berry, Sybouts, Whiteshore, and Horseshoe Lakes. The chimneys in Ceylon and Lydden Lakes range from less than 2 m to 9 m in depth and up to 50 m² in surface area. They generally have steeply sloping to vertical walls with overhangs and ledges at depth (Fig. 6).

Monitoring of the pits in Ceylon and Lydden Basins since 1981 shows that solution and refilling of these pipes may be extremely rapid and complex processes. The chimneys may be filled with either freshwater or highly saline brine depending on the time of year and the hydrologic conditions within the basin. The water columns in the chimneys may be either well mixed or thermally and chemically stratified. Two of the pits in Ceylon Lake and one in Lydden Lake formed within an

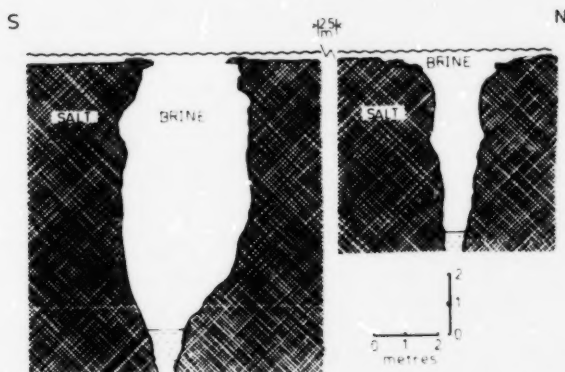


Figure 6. Morphology of selected solution chimneys in Ceylon Lake, July 1983.

18-month period during 1983-85. Conversely, one of the chimneys, originally 7.5 m deep, filled with over 5 m of crystal and mud in a two-year period.

Mud diapirism. Dykes and mounds composed of poorly sorted clastic material are commonly present in the salt-pan facies. The dykes occur in a range of sizes, with widths from several centimetres to about one metre. They are usually straight or very slightly curved, non-intersecting, and randomly oriented. The coarsest clasts in the dykes invariably have a preferred vertical orientation.

The intrusive mud mounds are usually small (less than 30 m² in area), low (less than 50 cm high), and roughly circular in shape on the floor of the salt pan. The clasts in the mounds, unlike those in the dykes, normally do not have a vertical fabric.

The poorly sorted sediment of both the dykes and mounds may be modified when brought to the surface of the playa. Sorting by wave action during high water-levels and by wind and sheetwash during subaerial exposure leaves a relatively coarse, well sorted gravel lag deposit on top of and immediately adjacent to the intrusion, and a sheet-like deposit of finer clastics away from the site. In places, this blanket of fine clastics covers large areas of the salt pan and is up to several centimetres thick.

These deformation structures are probably the result of liquefaction or fluidization of a water-saturated unit beneath the salt bed. The low permeability of the salt prevents diffusive pore-fluid escape which accompanies normal sediment compaction. With continued deposition and loading of the underconsolidated unit, weaknesses in the salt are eventually exploited, and the liquified sediment is injected into the salt bed until excess pore-fluid pressures are dissipated.

POSTGLACIAL EVOLUTION OF THE SODIUM SULPHATE LAKES

Water-level histories and geochemical evolution of the basins cannot be reconstructed as yet on a quantitative basis. Sediment fill in each basin results from a complex interplay of varying evaporation-to-precipitation ratios, quantity and chemistry of groundwater inflow, surface-runoff and drainage-basin characteristics, and major postglacial deformation. In particular, the implications of salt karsting

and mud diapirism to the stratigraphic interpretations have not been fully realized. However, the stratigraphy does record, in a general way, considerably differing depositional and hydrologic conditions and fluctuating water chemistries in several of the basins being studied.

Immediately after, or possibly concurrent with, the formation of a basin by meltwater from the retreating glacier or creation of a sinkhole by melting of buried ice, basal coarse clastic material was deposited by fluvial or sheetwash processes. Due to slumping of valley walls, differential isostatic rebound, and/or decreased meltwater flow, water gradually became ponded in the basins and lacustrine sedimentation began. Calcareous clay at the base of the lacustrine sections suggests a relatively fresh, low-Mg/Ca-ratio brine. High organic matter content, abundant shell material, and a general lack of lamination indicate high levels of productivity and the presence of bottom-dwelling organisms in this early phase. Carbonate-rich springs discharging into the lakes probably built small tufa mounds and carbonate-debris blankets in several of the basins.

Gradually, in response to the drier and warmer climatic conditions that prevailed over the prairies beginning about 8000 years ago, water levels in the basins dropped and concentration of brines increased. Carbonate hardgrounds, gypsum laminae and intrasedimentary salts suggest periodic desiccation and exposure. Initially, relatively deep, chemically stratified water bodies may have existed in selected basins as suggested by Grossman (1968). However, climatic and hydrologic conditions probably soon deteriorated to support only very shallow, playa-type lakes when most of the salt unit was deposited. Upward increase in soluble salt versus clastics points to an increase in salinity with time. The change from black, silty clay upward into the salt unit marks a transition from a mud-dominated playa to a salt playa. The upward increase in Mg-bearing salts at the expense of mirabilite in several of the basins suggests a shift in overall brine chemistry from a Na-dominated system to one of mixed Mg and Na.

Detailed chronological control has not yet been established for most of the basins so that little can be said of the duration of these changes. Presence of relatively thick salt units implies that hypersaline playa conditions existed for some time. Prolonged intervals of warm dry years may have resulted in dry lake conditions, desiccation, and possible erosion of the upper sediments of the salt pan. Wind and sheetwash transported clastics that periodically blanketed the basin, effectively decreasing the amount of salt dissolution during the next wet phase. Eventually, with climatic moderation about 3500 years ago accompanied by a more favourable hydrologic budget, shallow (and in some cases relatively deep) water conditions returned to the basins.

REFERENCES

- Barry, G.S., 1986, Sodium sulphate: Canadian Mining Journal, v. 107, no. 2, p. 77
- Barry, G.S., J.A. Boucher, and M. Prud'homme, 1985, Other industrial minerals: Canadian Mining Journal, v. 106, no. 2, p. 82-83.
- Broughton, P.L., 1984, Sodium sulphate deposits of western Canada, in G.R. Guillet and W. Martin, eds., The

- Geology of Industrial Minerals in Canada: Canadian Institute of Mining and Metallurgy Special Volume 29, p. 195-200.
- Cole, L.H., 1926, Sodium sulphate of western Canada - Occurrence, uses, and technology: Canadian Department of Mines Publication No. 646, 160 p.
- Christiansen, E.A., 1967a, Collapse structures near Saskatoon, Saskatchewan, Canada: Canadian Journal of Earth Sciences, v. 4, p. 757-767.
- Christiansen, E.A., 1967b, Preglacial valleys in southern Saskatchewan: Saskatchewan Research Council Map No. 3.
- Christiansen, E.A., 1971, Geology of the Crater Lake collapse structure in southeastern Saskatchewan: Canadian Journal of Earth Sciences, v. 8, p. 1505-1513.
- Christiansen, E.A., 1979, The Wisconsin deglaciation of southern Saskatchewan and adjacent areas: Canadian Journal of Earth Sciences, v. 16, p. 919-938.
- CNC/IHD (Canadian National Committee for the International Hydrologic Decade), 1978, Hydrologic atlas of Canada: Fisheries and Environment Canada, 75 p.
- Egan, D.M., 1984, Mineralogical and geochemical aspects of saline lake sediments of the northern Great Plains: M.Sc. thesis, University of Manitoba, Winnipeg, Manitoba, 129 p.
- Egan, D.M., 1986, The occurrence of scarbroite at Muskiki Lake, Saskatchewan, Canada: Mining Magazine, v. 50, p. 180.
- Freeze, R.A., 1969, Regional groundwater flow — Old Wives Lake drainage basin, Saskatchewan: Inland Waters Directorate, Scientific Series no. 3, 243 p.
- Grossman, I.G., 1968, Origin of sodium sulfate deposits of the northern Great Plains of Canada and United States: United States Geological Survey Professional Paper 600-B, p. B104-B109.
- Hardie, I.A., J.P. Smoot, and H.P. Eugster, 1978, Saline lakes and their deposits: a sedimentological approach, in A. Matter and M.E. Tucker, eds., Modern and ancient lake sediments: Blackwell Scientific Publications, Oxford, p. 7-41.
- Last, W.M., 1984, Sedimentology of playa lakes of the northern Great Plains: Canadian Journal of Earth Sciences, v. 21, p. 107-125.
- Last, W.M., and T.H. Schweyen, 1983, Sedimentology and geochemistry of saline lakes of the Great Plains: Hydrobiology, v. 105, p. 245-263.
- MacWilliams, W.A., and R. G. Reynolds, 1973, Solution mining of sodium sulfate: Canadian Institute of Mining and Metallurgy Transactions, v. 76, p. 127-131.
- Meneley, W.A., E.A. Christiansen, and W.O. Kupsch, 1957, Preglacial Missouri River in Saskatchewan: Journal of Geology, v. 65, p. 441-447.
- Rueffel, P.G., 1968, Development of the largest sodium sulfate deposit in Canada: Canadian Institute of Mining and Metallurgy Bulletin, v. 61, p. 1217-1228.
- Slezak, L.A., and W.M. Last, 1985, Paleoclimate and paleohydrology of saline lakes: implications of modern studies in the Northern Great Plains (Abstract): CANQUA Symposium on Paleoenvironmental Reconstruction of Late Wisconsin and Holocene, Program with Abstracts, p. 56.
- Sloan, C.E., 1972, Groundwater hydrology of prairie potholes, North Dakota: United States Geological Survey Professional Paper 585-C, 28 p.
- Stalker, A., 1961, Buried valleys in central and southern Alberta: Geological Survey of Canada Paper 60-32, 13 p.
- Tremblay, J.Y., 1984, Industrial minerals: Canadian Mining Journal, v. 105, no. 2, p. 85-87.
- Wallick, E.I., and H.R. Krouse, 1977, Sulphur isotope geochemistry of a groundwater generated $\text{Na}_2\text{SO}_4/\text{Na}_2\text{CO}_3$ deposit and the associated drainage basin of Horseshoe Lake, Metiskow, east-central Alberta, Canada: Proceedings of the Second International Symposium on Water-Rock Interaction, Strasbourg, p. 1156-1164.
- Weisman, W.I., and C.D. Tandy, 1975, Sodium sulphate deposits, in S.J. Lefond, ed., Industrial minerals and rocks, 4th edition, American Institute of Mining and Metallurgy, Petroleum Engineering Inc., New York, p. 1081-1093.
- Whitaker, S.H., and D.E. Pearson, 1972, Geological map of Saskatchewan: Saskatchewan Research Council, Saskatoon, and Saskatchewan Department of Mineral Resources, Regina.

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THE BIG QUILL LAKE SULPHATE OF POTASH PROJECT

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ABSTRACT

The Potash Corporation of Saskatchewan, through its wholly-owned production subsidiary, PCS Mining, has extensive ore reserves in Saskatchewan and is a major producer of potash fertilizer. Saskatchewan potash is marketed in various forms of muriate of potash (KCl) largely for agricultural fertilizers. In an effort to diversify and exploit the resources of the province, PCS undertook research in the production of sulphate of potash (K_2SO_4) which resulted in the commissioning of a 30,000-tonne per annum demonstration-scale facility at Cory Division in 1985. This facility uses the Glaserite process to convert Glauber's salt from Palo and potassium chloride from the Cory Division mine into sulphate of potash (SOP). Subsequent research developed a new process suitable for using low-concentration sulphate brine such as is found in Big Quill Lake and potassium chloride from one of the Corporation's divisions to produce SOP.

BIG QUILL LAKE — THE RESOURCE

Whiting (1977) studied Big Quill Lake which forms a large resource of sodium and magnesium sulphate in a relatively low-concentration brine, and compiled the data shown in Tables 1 and 2.

The lake is large, spanning 31 km north-south and 20 km east-west, and shallow, generally not more than two metres deep. Geographically, it is located on Highway 16 almost equidistant from Regina, Yorkton and Saskatoon. It is about 60 km from PCS Mining Lanigan Division via Highway 16 (Fig. 1).

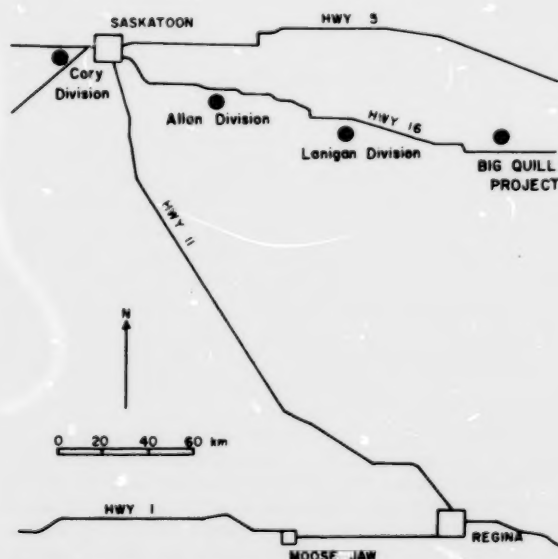


Figure 1. Location of Big Quill Lake.

Table 1. Big Quill Lake brine analysis, September 6, 1973 (Whiting, 1977).

Component	Concentration (ppm)
SO_4	29,400
Cl	3,410
HCO_3	359
CO ₂	121
Na	8,120
Mg	4,400
K	506
Ca	126
pH	8.28
Specific gravity	1.036

Table 2. Big Quill Lake: estimated tonnes of dissolved salts (Whiting, 1977).

Salt	Weight (tonnes)
$MgSO_4$	9,094,000
Na_2SO_4	7,140,000
NaCl	2,426,000
K_2SO_4	480,000
CaSO ₄	313,000
NaHCO ₃	263,000
Na_2CO_3	73,000
Total salts	19,789,000

Lake elevation: 1,688.6 ft or 514.7 metres

Lake volume: 14.83×10^9 ft³ or 0.42×10^9 m³

BIG QUILL PROCESSING PLANT

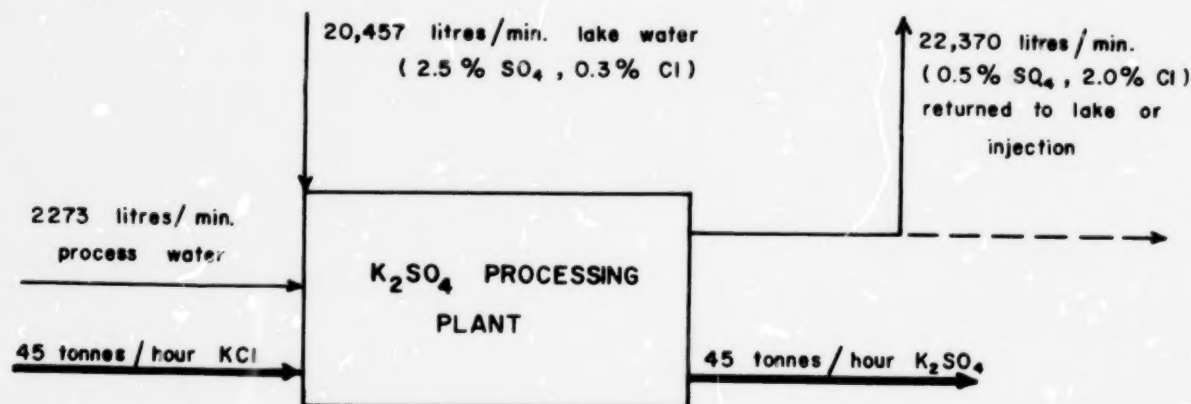


Figure 2. Process flows based upon an annual production of 300,000 tonnes of sulphate of potash (diagram reproduced from Environmental Impact Study).

THE PROCESS

Sulphate of potash production procedure (Fig. 2) begins with pumping of some 20,000 litres per minute of lake brine through a process where sulphate ions are exchanged with chloride ions from the KCl. The spent lake brine containing the chloride is then discarded back into the lake, and the saturated potassium sulphate brine is crystallized to form K_2SO_4 product. Finally, crystalline SOP is centrifuged, dried, sized and stored ready for shipment. Applications for process patents have been submitted, so the author is not free to discuss the process in more detail.

DEVELOPMENT

In order to develop the project, the process required proving further, suitable property had to be acquired along with mineral and water rights, an environmental assessment program had to be undertaken, and engineering studies had to be initiated.

Analysis of Big Quill Lake and of available facilities indicated that the south shore (Fig. 3) was the best site for a processing plant because:

- 1) it gives excellent access to relatively deep water suitable for pumping requirements,
- 2) Highway 16 provides convenient access to the south shore,
- 3) the CPR passes along the south shore between Kandahar and Wynyard,
- 4) power can be supplied from a 72 kV power line a few kilometres south of the lake, and
- 5) the shoreline rises rapidly, climbing well above the possible high-water mark.

Consequently, efforts were made to option appropriately located property. Two options were obtained, one near Kandahar and the second near Wynyard (Fig. 4).

At the same time, applications were made to Saskatchewan Energy and Mines under the Alkali Salts Regulations and to the Saskatchewan Water Corporation for rights to the minerals and waters of Big Quill Lake.

To prove the process, a pilot plant was set up in Saskatoon and testing commenced.

An engineering consultant was commissioned to prepare a preliminary plant layout for a 300,000-tonne per annum commercial facility and to provide a capital estimate.

An application to allow the project to proceed was made to Environment Saskatchewan, which decided an environmental impact assessment was first required. Studies were commissioned from Saskatchewan consultants to consider the effects of the proposed plant facilities upon the environment. Several meetings were held with local officials to describe the project and brief them on our intentions. Public meetings were also held to discuss the proposal and to receive (and respond to) questions and objections. Upon completion of the consultants' studies, a public meeting was held to report the results of those studies. In 1986, the necessary formal approval was obtained from the Minister of the Environment.

During the environmental engineering studies, a selection was made between the two optioned properties and the one nearest Wynyard was allowed to elapse.

The pilot plant in Saskatoon was successful, so equipment capable of producing one tonne per day of SOP was commissioned, and a pilot plant built at the Big Quill Lake site. As a result, arrangements were made with the rural municipality to upgrade the "beach road" to the site to supergrid status. PCS agreed to pay a portion of the cost and to guarantee the entire cost if the project is cancelled. Arrangements were also made for power to be temporarily supplied. The pilot plant was designed, built and

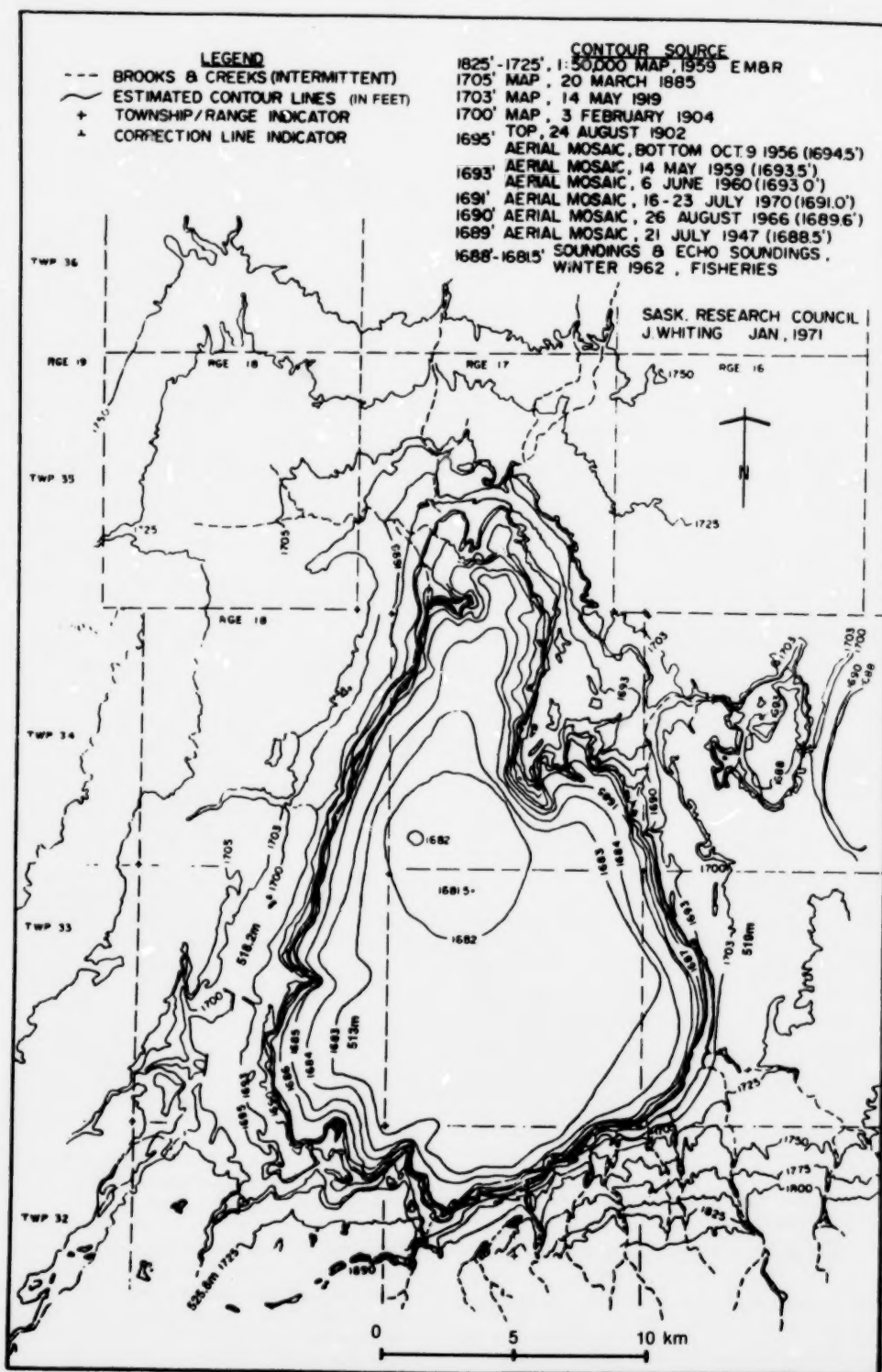


Figure 3. Bathymetry of Big Quill Lake with surrounding topography.

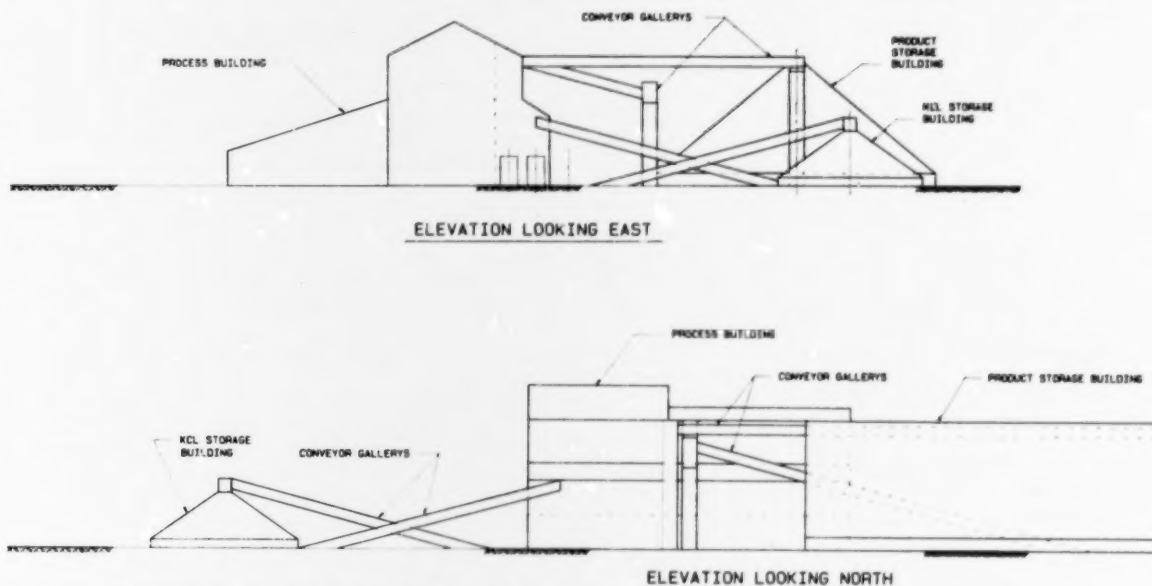


Figure 6. Elevation of proposed potassium sulphate plant at Big Quill Lake.

The anticipated construction period is 18 months with construction manpower peaking at about 250 men (Fig. 7). The total cost is expected to be close to, but less than, \$100 million.

PRESENT STATUS

The pilot plant was successfully operated from October 1985 to July 31, 1986. Operation of the process equipment has been optimized and the flow sheet has been revised.

A feasibility study in preparation comprises the following program:

- 1) final analysis of the pilot plant work and flow sheet details, and preliminary equipment selection,
- 2) capital and operating estimates for commercial facilities based on the final flow sheet,
- 3) market studies to identify market opportunities and expected price and volume projections, and
- 4) financial analysis considering various production capacities.

CONCLUSION

A process has been developed, which is capable of exploiting a low-grade resource at Big Quill Lake along with output from existing potash mines, to manufacture a value-added product within the province. Basic requirements which are in place include selection of property, acquisition of alkali-salts and water licences, and obtaining of environmental approval. Pilot facilities, providing opportunities to optimize the process and test the market, have been built and studied.

The future development of a commercial SOP facility depends upon favourable forecasts from additional financial and market studies. The current depression in farm-produce

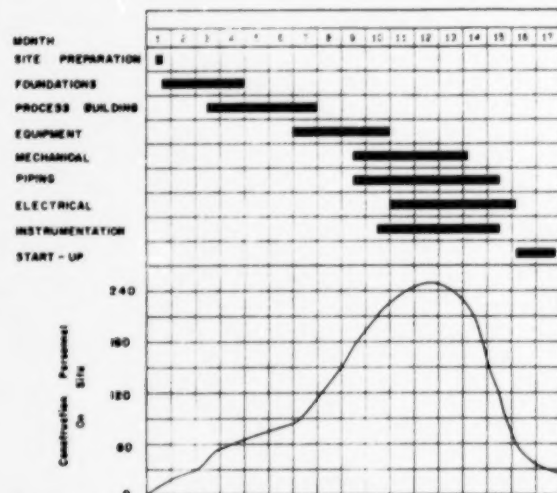


Figure 7. Scheduling and manpower requirements of proposed potassium sulphate plant at Big Quill Lake.

markets has led to a drastic downturn in fertilizer sales and prices. As a result, the author is convinced that dedicated efforts to reduce the cost of building and operating the facility are critical to the success of the project. He is equally convinced that the process is economically attractive and that a way will be found to produce and market SOP from the Big Quill Lake site.

REFERENCE

- Whiting, J.M., 1977, The hydrological and chemical balance of the Big Quill Lake Basin: Saskatchewan Research Council, Saskatoon.

LOCATION, EXPLORATION AND PRODUCTION OF GRAVEL RESOURCES IN SASKATCHEWAN

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ABSTRACT

Sand and gravel are nonrenewable mineral resources, the present annual value of which in Saskatchewan is about \$40,000,000. Their current yearly depletion rate in the province is approximately 15,000,000 tonnes. Our company records indicate that in southern Saskatchewan an estimated 10,000 gravel prospects have been mapped from airphotos in the past 40 years. Probably not more than one in a hundred deposits contains more than five million tonnes of granular material. In addition, even in the coarser parts of these deposits, the proportion of gravel suitable for crushing for coarse aggregate in concrete and for railway ballast for rail-bed upgrading is usually small. However, many of the 10,000 prospects contain material that is suitable for traffic gravel on roads built and maintained by rural municipalities, the largest consumer of sand and gravel in the province. Unfortunately, a large number of the smaller prospects, which have an average distribution density of about one per 25 km², remain unknown to potential users. Also, gravel users are sometimes unaware of deposit depletion and of the savings that can result from discovering and developing deposits closer to the point of usage. The fastest and cheapest way of inventorying gravel resources in Saskatchewan begins with the interpretation of 1:80,000 scale stereophotos followed by ground reconnaissance and spot examination at key locations, then — where warranted — by some combination of geophysical, auger and backhoe exploration.

GRAVEL AS AN ECONOMIC MINERAL RESOURCE

A recent European study of gravel resources and reserves (Luttig, 1986) clearly documented the importance of gravel as a mineral resource. Luttig's list of the world's 30 most widely used, valuable resources in 1977 included energy resources, metallic raw materials, and non-metallic raw materials. The author showed graphically that gravel aggregate in Europe ranked first in terms of quantity used, and third (behind oil and hard coal) in terms of dollar value.

GRAVEL SEARCHES FROM AIRPHOTOS

Our company's gravel-search records cover the 40-year period from 1946 to 1986. They show that approximately 700 airphoto interpretation studies have been made in search of sand and gravel deposits across Canada. Altogether, an estimated 65,000 sand and gravel prospects have been mapped for governments and for industry. Of these prospects, about 10,000 are located in the agricultural area of southern Saskatchewan. Many of the prospects identified from airphotos are small in size, covering a few hectares only. Because sand and gravel are nonrenewable resources and are often in great demand, a large number of these smaller deposits have already been depleted or nearly depleted, enhancing the importance of the fewer but much larger sand and gravel deposits.

Interest in locating gravel prospects mapped from airphotos in Saskatchewan is indicated by the number of requests, about 25

a year, that we receive for granular material searches. Search areas vary in size from a minimum of about 100 km² upward to a few thousand square kilometres.

GEOLOGICAL OCCURRENCE OF GRAVEL DEPOSITS

Landforms containing the smaller sand and gravel occurrences in southern Saskatchewan include kames, kame deltas, kame terraces, eskers and crevasse fillings — all knobby to ridgy, ice-contact glaciofluvial deposits — in addition to small outwash deposits. The larger granular deposits are generally found in kettled and nonkettled outwash plains, valley trains, and glacial deltas — all proglacial meltwater stream deposits. Some postglacial alluvial terrace and channel deposits are also very large and, in places, become extremely coarse. Any of these landforms may contain a large proportion of sand or, much less frequently, a high proportion of coarse gravel. Ice-contact deposits tend to be more variable and more complexly stratified than other types of deposits and bedding has frequently been disturbed as a result of the melting of underlying or adjacent blocks of ice.

Most small granular deposits in Saskatchewan are oversanded, necessitating screening out of some sand fractions to upgrade the product for use. Accordingly, a photo interpreter must try to identify correctly the gravel-bearing landforms and predict the gradation of material in them. The interpreter should also outline the extent of a prospect and qualitatively forecast its

probable depth. To carry out this work, the interpreter looks for and needs to find a number of airphoto-identifying features.

AIRPHOTO-IDENTIFYING FEATURES OF GRAVEL DEPOSITS

In some locations, only one gravel-identifying feature is present. More often, however, two or three features appear in 1:80,000 stereoscopic airphotos. Even then, diagnostic identifying features may be weakly expressed, so five or six distinctive clues are usually required to provide the interpreter with sufficient information about a given prospect. In Saskatchewan, the following airphoto-identifying features are most helpful.

Geomorphic settings and environments of deposition of sand and gravel. Examples are distinctly outlined gravel terraces and large deltas near, or at the downstream end of, abandoned glacial spillway channels. The interpreter pays special attention to geomorphic settings along the sides, bottoms and downstream parts of abandoned meltwater channels which carried large flows of water for short time-intervals some 10,000 years ago and which are perhaps the most fruitful environments for locating gravel sources in the province.

Micro-topographic details. These include anomalously steep slopes, and sharp intersection angles between level upland surfaces and the sides of stubby gullies and kettleholes. The slopes at these sites reflect steeper angles of repose of clean, cohesionless granular material.

Faint to distinct relict current markings and braided channel scars. In many places, these scars are obliterated by long-continued weathering and erosion unless the granular deposit is very coarse.

Sharply outlined and deeply depressed kettleholes in the deeper and coarser glaciofluvial sediments. To the experienced photo interpreter, kettleholes in glaciofluvial sediments nearly always differ from kettleholes in hummocky clayey till and clayey glaciolacustrine terrains, having a sharper, more distinct appearance.

Gully shapes in granular material. Distinctive three-dimensional shapes and cross-sections, subequal spacings, stubby appearances, and characteristic physiographic settings are all potential indicators of sand and gravel deposits.

Details of tonal patterns associated with microrelief variations. Dappled tapioca-like tonal patterns on freshly summerfallowed fields are often characteristic of underlying granular deposits. Interlacing darker toned relict channels on coarse gravelly outwash plains occur along depressions that have higher moisture and organic contents than adjacent, slightly elevated, plateau-like braid bars.

Type of land use. An existing gravel pit indicates that granular material is present and should be checked as it may be a small pit in a large untested gravel deposit. Because subsoils in granular deposits have low moisture-retention capacities, they tend to produce significantly

lower crop yields in semiarid or arid climates. Consequently, many gravel deposits are found below pasture land rather than under cultivated land.

Natural vegetation. Vegetation patterns and vegetative types are interpreted in the light of texture of near-surface material, local surface drainage and climate. Native grassland vegetation is usually much lighter toned and more uniform in appearance over granular deposits than over fine-grained lacustrine and till deposits because subsurface drainage conditions are more uniform.

With time, the airphoto interpreter becomes increasingly familiar with gravel-recognition features and with slight variations in their appearance in airphotos.

In Saskatchewan and across the Canadian Prairies generally, granular deposits are notoriously high in sand sizes. Large, deep, coarse gravelly deposits are scarce, averaging approximately one in every hundred deposits located. Accordingly, the interpreter searches for features that reveal larger, deeper, and coarser glaciofluvial and alluvial deposits. These features include well expressed current and channel markings, anomalously steep sides on kettleholes, V-shaped stubby gullies, and abrupt changes in slopes around the upper sides of kettleholes and where deeper channel scars occur in granular deposits.

The stratigraphic variability of granular deposits and the chances of finding poor-quality rock particles can often be inferred from a proper appreciation of the environment of sand and gravel deposition. For example, where granular deposits occur within and adjoining the upper sides of valleys excavated through glacial drift into clay shale, the resulting granular materials are usually contaminated by abundant shale fragments. Such contamination is characteristically highly deleterious in concrete.

REMOTE-SENSING SEARCH METHODOLOGIES

FROM AIRPHOTOS

Mapping sand and gravel deposits from airphotos has been routine practice for several decades, and the methodologies followed are fairly well known (Mollard and Dishaw, 1958; Mollard, 1962; Mollard et al, 1967). After search-area boundaries and aggregate-quantity and -quality requirements are known, several scales and ages of stereoscopic airphotos are assembled. In addition, agricultural-soil-survey, surficial-geology, bedrock-geology, groundwater, topographic, land-use, and land-capability maps of the study area should be obtained (along with other appropriate specialized maps if available) for purposes of correlation, confirmation, and supplying supplementary information.

All delineations are made on the airphotos from stereoscopic study. Annotations record the interpreter's predictions about the mode of deposition, the quantity, the quality and the variability of suspected sand and gravel prospects. They also indicate the best places to explore in the field, and the chances of a prospect's meeting specific user requirements. The outlines of individual prospects and the annotated information about each may then be transferred to a key map of the search area. Xeroxed airphotos showing prospect information are

usually referenced to small-scale mosaics, photo index sheets, or planimetric maps. A covering report accompanies the maps, tables and annotated airphotos.

Owing to variations in prospects mapped, data about predicted gradation and variability, inferred water table position, and estimated recoverable volume in cubic metres or tonnes are, in general, tabulated. The chances of an airphoto-identified prospect's meeting specified quantity and quality requirements are usually evaluated qualitatively. In addition, the order in which prospect exploration should be conducted is recommended. Here, an identified prospect should be clearly distinguished from a confirmed gravel deposit. The term "deposit" is used to describe a confirmed source of sand and gravel, proven with respect to both quantity and gradation. The term "prospect" is used to describe a potential source of sand or gravel that has not been tested or proven. The quantity and gradation of material is therefore inferred. Prospects may be identified from airphoto study, field reconnaissance, borehole data, or a combination of these. Nowadays, high-altitude (small-scale) airphotos are commonly interpreted for initial identification of sand and gravel prospects. For this, so-called LIFT (Lower Inventory for Tomorrow) airphotos are almost always used. They were taken in 1970 using an 88.85 mm (3.5 inch) focal length camera. Minor, but highly diagnostic, relief details are therefore greatly exaggerated. Because the scale is small — approximately 1:80,000 — up to 335 km² of landscape are available for three-dimensional viewing in a single picture. The LIFT airphotos cover the entire agricultural area of western Canada, and were taken to measure summerfallowed land that qualified for government payment on lands kept out of crop production that year. Although LIFT airphotos have proved excellent for the detection of all types and sizes of granular deposits, their interpretation is frequently followed by re-examination of the identified prospects in larger scale stereophotos.

FROM SPACE IMAGERY

An experiment designed to evaluate the capabilities of 1:500,000 scale Thematic Mapper (TM) imagery for visually identifying large gravel deposits was carried out in 1985 (Mollard, 1985). The results suggest that only the very large gravel prospects are inferable from regional geomorphic settings, and from land-use and land-cover features identifiable in the imagery. As the margins of these prospects are usually poorly defined, they can be only tentatively delineated. Lack of the three-dimensional view provided by stereoscopic aerial photographs hinders confident outlining of prospect margins and prediction of recoverable depths to obtain estimates of material volume (typically in the order of 1×10^4 to 1×10^5 metre³ per metre of recoverable depth in large granular deposits).

The principal advantage of TM imagery is one of scale. Approximately 1200 contact airphotos must be obtained in order to cover the same 32,500 km² area that is shown on one TM image. Blowups of recent TM imagery may be used to disclose new gravel pits or enlargements of old ones, where material has been extracted. As a result, TM imagery may be used to update inventories of large deposits having open pits in them (Mollard, 1985).

Interpretation of stereoscopic airphotos is always a necessary follow-up to interpretation of TM imagery to:

- 1) locate with generally acceptable accuracy the boundaries of TM-identified deposits,
- 2) observe smaller features that may offer diagnostic clues to their coarseness, thickness, water table position, and deposit variability, and
- 3) select the best localities in which to conduct field tests.

FIELD EXPLORATION METHODOLOGIES

FIELD-RECONNAISSANCE EXAMINATIONS

Depending on the study objectives, field reconnaissance of identified prospects may be all that is done. For full evaluation of larger gravel prospects, however, field reconnaissance should be followed by geophysical exploration, then by auger or backhoe testing (Mollard et al, 1967).

GEOPHYSICAL-EXPLORATION TECHNIQUES

Geophysical techniques are often the quickest and least disruptive way of determining:

- 1) whether or not a potentially viable sand or gravel deposit exists, and
- 2) if such a deposit does exist, quantitative information about the thickness of overburden and of granular material. An electrical resistivity survey is a frequently used geophysical method.

Electrical-resistivity survey techniques are commonly categorized according to whether or not they require electrical ground-contact. Those that require such contact are called galvanic techniques, and tend to be slow and, therefore, costly for surveying extensive sand and gravel prospects.

Instruments have been developed to measure electrical conductivity without the need for electrical contact with the ground. They include the EM 31 and EM 34 which allow their operators, moving at walking pace, to measure conductivities of subsurface soil materials to various depths.

In the EM 31 side-mode position, the measured apparent conductivity gives subsurface conductivities to depths of approximately three metres, whereas in the up-mode position an investigation depth of approximately seven metres is obtained. The EM 31 instrument is therefore usually satisfactory where relatively thin granular deposits and thin overburden are suspected. For prospects having thick overburdens, and where the underlying granular materials are expected to be thick as well, EM 34 equipment is used (Hardy Associates (1978) Ltd.).

TRUCK-MOUNTED-AUGER EXPLORATION

A truck-mounted auger is often used to explore sand and gravel deposits. The 10- to 15-cm-diameter augerholes create little or no land damage. Although auger sampling seldom provides good material for laboratory testing, it can be used to verify quickly the existence of granular material at a prospect, and to determine deposit depth, variability and extent. Auger testing is usually carried out after geophysical surveys and before backhoe exploration.

BACKHOE EXPLORATION AND TESTING

Backhoe testing is generally the last and most reliable type of exploration. It provides good-quality, large-volume samples,

and visual appraisal of deposit stratification and variability. Also samples of individual strata of pure sand, coarse gravel, or mixed sand and gravel can be collected from the walls of open testpit sites.

AGGREGATE QUALITY IN SASKATCHEWAN

The commonest and most important quality limitation on natural construction aggregate in Saskatchewan is, perhaps, deposit gradation. The majority of ice-contact and small outwash deposits are oversanded, containing 70 to 80 per cent sand-sizes and very little gravel over the two- to five-cm-size. This feature restricts the usefulness of many small deposits, few of which provide material acceptable in large-scale ready-mix concrete or in railway ballast. Nevertheless, the smaller, sandier deposits may possess an acceptable gradation for subbase and base material for highways and for traffic gravel on roads in rural municipalities, the main consumers of gravel in the province. For good-quality concrete and crushed railway ballast, the main deleterious substances are siliceous shale, clay lumps, clay ironstone, soft or friable sandstone, and some weathered argillaceous dolomitic limestones. Weathered coarse-grained micaceous crystalline rocks such as coarse granites, biotite gneisses and mica schists are also detrimental as they generally become crumbly and liable to break down readily, especially if they lie within the zone of water-table fluctuation. Lime and iron-oxide coatings may be a concern, particularly where they are extensive and moderately well bonded to the mineral aggregate, and are not removed during crushing or screening. The content of fines and gap grading are other constraints typical of extensive in situ and re-transported Tertiary gravels near the Canada-US border, as well as some other deposits scattered across the province.

Perhaps the most widespread deleterious aggregate in concrete in Saskatchewan is siliceous (opaline) shale derived from the Olanah Member of the Cretaceous Riding Mountain Formation. Fine-grained amorphous silica in this shale chemically reacts with alkalis in the cement producing 'popouts' where fragments of this shale are close to the surface of concrete driveways, sidewalks and structure foundations. In addition, opaline shale is so highly absorbent that concrete subjected to cyclic freezing and thawing undergoes rapid physical deterioration. Where shale particles are a problem, they can be removed by a shale-shaker.

Some argillaceous dolomitic limestones and dolostones are also absorbent, and are therefore susceptible to physical deterioration from repeated freeze-thaw cycles.

Despite these local aggregate quality problems, many large granular deposits in Saskatchewan contain good-quality aggregate when crushed, washed, and sized.

DISTRIBUTION, COST AND DEPLETION OF GRAVEL SUPPLIES IN SASKATCHEWAN

In the absence of any complete long-term statistical records, we have relied heavily on our airphoto studies and past field experience to develop some estimates of gravel distribution in Saskatchewan. The intent is to give some basic, order-of-magnitude information for comparisons and projections.

We estimate that, in the past 30 years, our firm has mapped about 10,000 sand and gravel prospects in southern Saskatchewan. Many of the prospects identified from airphotos 20 to 30 years ago were small in volume. Re-interpretation of these areas in the late 1970s and early 1980s revealed that a percentage of them, usually located close to places where the gravel is required, have been essentially depleted. As a result, the discovery and development of large aggregate sources which are increasingly distant from points of material-usage grow ever more necessary. On average, about one small granular-material prospect is located in any given 26-km² area. Most of the larger gravel deposits contain from 2.5 to 12.7 x 10⁶ tonnes, and the largest deposits about one billion tonnes. On a total volume basis, the largest deposit is estimated to contain more granular material than has been consumed in all Saskatchewan during the past century. Five or six gravel deposits in the next smaller category may provide a similar amount of granular material. Accordingly, the chance of running out of gravel in the near future is low.

The critical concern is the gravel's erratic distribution, which affects haul costs. The ever-increasing costs of trucking gravel over lengthening distances become apparent upon realization that, on average, each of the 300 rural municipalities (RMs) in Saskatchewan uses about 15,200 m³ of traffic gravel per year on their road network and spends about \$0.18 to haul one cubic metre of gravel one kilometre after the gravel has been loaded onto trucks. So the total cost of hauling traffic gravel one extra kilometre works out to an annual expenditure of about \$820,000.

The smaller gravel sources in the province are mainly depleted through exploitation by rural municipalities. The larger deposits are thus becoming increasingly important as a natural mineral resource and reserve in Saskatchewan's economy, their most serious disadvantage being their scattered distribution.

PRODUCER SHIPMENTS OF AGGREGATE IN SASKATCHEWAN

Statistics showing gravel aggregate shipments appear in annual record books (see Statistics Canada, various years; Tables 1 and 2). In Saskatchewan, the five major sand and gravel consumer groups in order of volume-of-material used each year are:

- 1) rural municipalities,
- 2) the provincial Department of Highways and Transportation,
- 3) the CN and CP Railways,
- 4) ready-mix concrete contractors, and
- 5) contractors undertaking major-facilities projects.

Tables 1 and 2 show Canadian Minerals Yearbook annual figures for the total tonnes of sand and gravel shipped in Saskatchewan for the years 1969-84 and the total value of shipments in the years 1980-84. The producer shipment figures provided by Statistics Canada are well below user consumption figures published by the Saskatchewan's Department of Rural Development (compare Tables 1 and 3 for the year 1981). A possible explanation for this discrepancy is that only a portion of all gravel transported in the province is reported to Statistics Canada.

Table 1. Total weight of producer shipments in Saskatchewan 1969-84 (Canadian Minerals Yearbook).

Year	Total weight of producer shipments ('000s tonnes)
1969	6,975
1970	8,148
1971	10,291
1972	7,738
1973	6,214
1974	10,741
1975	8,313
1976	8,619
1977	9,135
1978	11,935
1979	10,232
1980	9,828
1981	7,909
1982	8,512
1983	7,999
1984	9,500

Table 2. Total value of producer shipments in Saskatchewan, 1980-84 (Canadian Minerals Yearbook).

Year	Total value of producer shipments (\$'000s)
1980	21,976
1981	18,405
1982	20,037
1983	21,014
1984	25,550

USER CONSUMPTION OF AGGREGATE IN SASKATCHEWAN

Estimates of user consumption of sand and gravel in Saskatchewan (Table 3) are taken from the province's Department of Rural Development, Planning and Research Branch Report, December 1981. These, the most recent such figures available, are about double the producer-shipment weight recorded in the 1981 Canadian Minerals Yearbook (Table 1).

Using Saskatchewan's Department of Rural Development's 1981 estimate of 15 million tonnes worth \$2.33* a tonne, the total value of natural sand and gravel aggregate used in Saskatchewan in 1981 appears to have been about \$35 million dollars. For 1986, five years later, the total value is likely to exceed \$40 million dollars.

Table 3. Estimate of user consumption of sand and gravel in Saskatchewan in 1981.

Sand and gravel consumer	Total weight used ('000s tonnes)
Rural municipalities	7,988
Saskatchewan Highways	4,983
Private users (cities, ready-mix-concrete contractors and others)	2,153
Total quantity consumed	15,124

FUTURE NEEDS

Estimates of current usage and a projection of future aggregate requirements to the year 2000 together suggest that southern Saskatchewan has sufficient reserves of sand and gravel to satisfy demands through the next few centuries. The deposit with the largest total volume of granular material (out of 100 or so large sand and gravel deposits in southern Saskatchewan) is considered to contain sufficient material to have supplied the province's entire requirements for the past century. The five or six next-largest deposits would probably have done likewise. The critical concern in Saskatchewan is not, therefore, the lack of gravel, but the latter's poor distribution and resultant increased haulage costs. Using an average consumption-volume increase of four per cent a year from Figure 1, and starting with the 1981 figure of 15×10^6 tonnes, the aggregate consumption in Saskatchewan to the year 2000 is projected in Table 4.

Table 4. Projected aggregate consumption in Saskatchewan to Year 2000.

Year	Millions of tonnes
1981	15.0
1982	15.6
1983	16.2
1984	16.9
1985	17.5
1986	18.2
1987	19.0
1988	19.7
1989	20.5
1990	21.3
1991	22.2
1992	23.1
1993	24.0
1994	25.0
1995	26.0
1996	27.0
1997	28.1
1998	29.2
1999	30.4
2000	31.6

* Calculated from the 1981 Canadian Minerals Yearbook's figures of 7909 million tonnes and 18,405 million dollars.

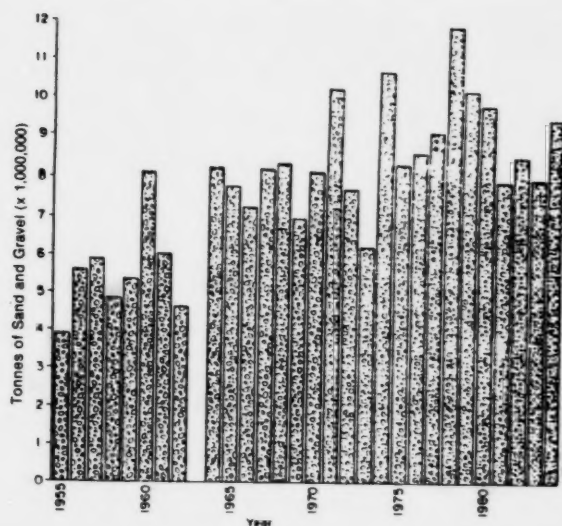


Figure 1. Producer shipments* of sand and gravel in Saskatchewan, 1955-84; average increase is about 4 per cent per year (plot provided by Saskatchewan Research Council, Saskatoon, using data from Canadian Minerals Yearbook).

The total estimated aggregate requirement for the period 1986 to 2000 is approximately 365 million tonnes (Table 4). To satisfy this requirement as economically as possible, a number of factors will require careful consideration in the future:

Airphoto mapping combined with follow-up exploration and testing of the larger granular deposits.

Although many of these gravel deposits appear on existing very-small-scale maps, they have not been outlined in detail for potential aggregate users. In fact, they may be unknown to many potential users. Some deposits occur within a few kilometres of existing transportation systems requiring aggregate. Others underlie these systems. Improved awareness of the existence, quantity and quality of these major gravel sources will become increasingly important as consumers' needs expand.

The necessity of longer aggregate hauls. As the province's gravel deposits diminish in number through being worked out, average haul distances will everywhere increase, often dramatically. The larger and more distant deposits will have to be used to make up local deficiencies. The best methods of handling and hauling aggregates over the longer distances therefore require careful study. Rail haul may have to be considered as an alternative to truck haul.

Exploration and use of the larger intertill (buried) deposits. In order to keep aggregate haul distances manageable, the discovery, exploration, and use of intertill deposits is expected to increase in the future.

These granular deposits may be overlain by four to six metres of till. If the buried granular material is sufficiently thick and the deposit extensive enough, these deposits could provide an alternative to longer hauls from widely spaced surface deposits. The development of intertill deposits would doubtless require the stripping of large volumes of overburden, a task that might be economically feasible using modern low-unit-cost earthmoving equipment. Buried intertill gravel deposits occur in the Dafoe, Regina, Kenaston, and Francis areas of Saskatchewan, and are expected at many other locations in the province. Some buried deposits may be inferred from an analysis of geomorphic setting coupled with the interpretation of subtle airphoto-identifying features. These deposits seem to be most common around the margins of former large glacial lakes. Minor glacial readvances over gravelly deltas that extended into temporary glacial lakes, may, for example, mask (but not entirely obliterate) the airphoto identifying features of these buried prospects.

REFERENCES

- Hardy Associates (1978) Ltd., no date, Mapping gravel deposits using electro-magnetic methods, in Hardy Associates (1978) Ltd., Brochure on geophysical techniques used in sand and gravel exploration.
- Luttig, G., 1968, Resources and reserves of European gravel deposits: Bulletin of the International Association of Engineering Geology, No. 33, April, p. 27-30.
- Mollard, J.D., 1962, Photo interpretation in prospecting for granular construction materials: Transactions of Symposium on Photo Interpretation, Uitgeverij Waltman, Delft, The Netherlands, v. 14, p. 514-523.
- Mollard, J.D., 1985, The utility of high resolution Landsat TM imagery in the identification of large sand and gravel prospects in south-central Saskatchewan, prepared for Canada Centre for Remote Sensing, Ottawa, Ontario.
- Mollard, J.D., and H.E. Dishaw, 1958, Ten years of mapping granular deposits from aerial photographs: Highway Research Board Bulletin No. 180, Highway Research Board, Washington, D.C., 11p.
- Mollard, J.D., M.F. Clark, and K.M. Stephenson, 1967, Exploration and development of sand and gravel aggregates in Saskatchewan, in Index '67 Proceedings, p. 207-223.
- Statistics Canada, various years, Canadian Minerals Yearbook: Production shipments by provinces and by users, with a breakdown by Statistics Section, Mineral Development Sector, Energy, Mines and Resources, Ottawa.

* These data probably include only gravel moved by Saskatchewan Highways, CP and CN Railways, and large contractors. They probably do not include production from many of the small gravel operations throughout the province.